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UNDERSTANDING RECENT VARIABILITY IN THE ARCTIC SEA ICE COVER – SYNTHESIS OF MODEL RESULTS AND OBSERVATIONS

by

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This thesis provides a continuation of the analysis of the diminishing sea ice trend in the Arctic Ocean by examining results from the NPS 1/12 degree pan-Arctic coupled ice-ocean model. While many previous studies have analyzed changes in ice extent and concentration, this research focuses on ice thickness as it gives a better representation of ice volume variability.

The skill of the model is examined by comparing its ice thickness output to actual sea ice thickness data gathered during the last three decades. The model comparison is made against the most recently released collection of Arctic ice draft measurements conducted by U.S. Navy submarines between 1979 and 2000.

The NPS model indicates an accelerated thinning trend in Arctic sea ice during the last decade. The validation of model output with submarine upward-looking sonar data supports this result. This lends credence to the postulation that the Arctic is likely to be ice-free during the summer in the near future. The diminishing Arctic sea ice will have significant implications for both the physical and operational environment in which the U.S. Navy currently operates.

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I. INTRODUCTION

A. IMPORTANCE OF ARCTIC SEA ICE RESEARCH

The effects of global warming on the Arctic Ocean finally gained the American public’s full attention in early 2007 with the release of the Intergovernmental Panel on Climate Change (IPCC)’s Fourth Assessment Report (AR4). The evidence of rising global temperatures leading to the loss of Arctic sea ice became the subject of news headlines that spring but the downward trend in sea ice thickness and areal extent has been observed and documented by scientists for the past decade. If this downward trend continues as expected, resulting in an ice-free Arctic summer, it will have far reaching impacts on global climate, ocean circulation, Arctic wildlife, international trade, energy resources, and geopolitics to name a few key areas of concern.

The effects of climate change around the world are often subtle, ambiguous, or region specific and frequently subject to debate. The Arctic regions, however, have seen the clearest evidence to date of the effect of rising temperatures on the environment. As a harbinger of global climate change, the most obvious manifestation has been in the seasonal decline of Arctic sea ice over the past decade. Of the wide-ranging ramifications of diminishing Arctic sea ice mentioned above, two of the most important impacts concern the role sea ice plays in the regulation of global weather and global ocean circulation (Meehl et al., 2007).

Therefore research on the rate and magnitude of sea ice loss is of vital importance in accessing the future effects of global climate change.

Arctic sea ice plays an important role in regulating global weather by maintaining the energy balance between arctic and mid-latitudes (Bourke and Garrett, 1987). Changes to the Arctic atmospheric and oceanic temperatures will lead to increased latent and sensible heat fluxes in the Arctic (Brass, 2002), resulting in greater incidence of cyclonic activity and precipitation (Meehl et al., 2007). In addition, mid-latitude storm tracks will shift and extend more northward as warmer waters advance to the sub-Arctic (Brass, 2002).

The observed global warming trend is most pronounced in the higher latitudes due to an effect known as the snow/ice-albedo feedback. The snow/ice-albedo feedback is a thermal feedback loop that is dependent on incoming solar radiation. Snow and ice have high albedo values which act like a mirror and reflect the majority of the incoming solar radiation back to space, rather than allowing it to be absorbed by the earth’s surface and atmosphere. In areas covered by snow and ice the high albedo values serve to maintain or lower the already cold (near freezing) surface temperatures which in turn facilitate increased snow and ice production. Liquid water and exposed land surfaces, however, have much lower albedo values than ice and snow resulting in more of the incoming solar radiation being absorbed by the environment. As global surface, oceanic, and atmospheric temperatures rise due to greenhouse gas loading, the amount of snow and ice cover at the poles and high altitude mountains will decrease due to increased melting thus exposing greater areas of lower albedo land and open water areas. The effect of global warming will result in a positive feedback loop wherein rising temperatures lead to increased amounts of open water and exposed land surfaces which lead to increased solar radiation absorption and consequently further melting of the snow and ice cover. The snow/ice-albedo feedback loop is described by Curry et al., (1995). In addition to the influence of ocean heat transport and polar cloud cover, the snow/ice-albedo feedback loop is a major contributing factor to the polar amplification of global warming as described by Holland and Bitz (2003). Understanding the rate at which the snow/ice albedo feedback loop is increasing is important for predicting the future state of the Arctic Ocean icepack and the resulting influence on global weather and climate.

In addition to affecting global weather patterns, melting Arctic sea ice also holds significant implications on global ocean circulation patterns. The world's oceans are interconnected via a large, global circulation pattern which, in very general and simple terms, can be described by the flow of warm, equatorial water poleward near the ocean surface and cold, dense water flowing from high latitudes equatorward along the seafloor. In reality, the circulation is more complex than this as it is driven by the ocean's thermohaline characteristics and continental and seafloor topography. This global ocean circulation pattern, or "Great Ocean Conveyor" as described by Broecker (1991), is driven by the sinking of cold, dense surface waters at two key formation areas – the North Atlantic and around Antarctica. Known as the North Atlantic Deep Water (NADW) and Antarctic

Bottom Water (AABW), the flow of these two water masses drives the global circulation of the world's oceans which serves to equalize the earth's energy balance by transporting heat from the equator to the poles, which in turn gets released to the atmosphere at higher latitudes. This transfer of heat energy is what moderates the earth's climate. Any change in the circulation of the ocean conveyor will have impacts on the climate as has been documented from core samples taken from Greenland icesheet (Broecker, 1991).

The formation of North Atlantic Deep Water occurs in the Labrador Sea and in the Nordic Seas where northward flowing, high salinity Atlantic water is cooled to the point where its density causes it to sink (Broecker, 1991). The sinking of this northward flowing stream of water is highly susceptible to changes in the upper ocean density. If the upper ocean salinities in the North Atlantic are lowered by the addition of freshwater, sinking either will not occur or it may only descend to an intermediate depth. In either case the formation of NADW may be significantly reduced or cease causing one of the key drivers of the global ocean conveyor to shut down (Toggweiler, 1994). Changes in salinity of North Atlantic surface waters due to freshwater influx come from three primary sources: increased high latitude precipitation, river and glacial runoff, and melting sea ice. Evidence of the freshening of the North Atlantic waters over the past 40 years has been documented by numerous studies (Dickson et al., 2002; Curry et al., 2003; Curry and Mauritzen, 2005) although the exact contribution of each of the primary freshwater sources and their predicted increases due to global warming has not been definitively determined. Computer models have shown however, that increased influx of freshwater can shut down the formation of NADW and the ocean conveyor (Broecker, 1991; Toggweiler, 1994). The disruption of the formation of NADW and its contribution to the global ocean conveyor holds significant impact on the global climate, especially for northern Europe which is kept 5-8° C warmer than it would be based on latitude alone (Broecker, 1991). Understanding the rate of Arctic sea ice melt and its influence on the freshwater influx to the North Atlantic is essential to understanding the consequences of climate change on global ocean circulation.

B. CURRENT STATE OF ARCTIC SEA ICE THICKNESS RESEARCH

Numerous studies have documented the annual decline of Arctic sea ice extent since 1978 which now stands at about -4% per decade (Sturm et al., 2003; Serreze et al., 2003, Stroeve et al., 2005; Francis et al., 2005; Stroeve et al., 2007; Serreze et al., 2007) with significantly larger losses of -8.6% per decade observed at the end of the summer melt season (Serreze et al., 2007). The state of Arctic sea ice thickness, however, has been more challenging to assess.

Accurate estimates of Arctic sea ice thickness have been difficult to obtain due to the limited data collection methods available to scientists and researchers resulting in a paucity of extensive observational datasets. Ice core samples are the most precise method but collection sites have been limited across the Arctic in both spatial and temporal extent (Bourke and Garrett, 1987). Additionally, ice core sampling is a laborious and logistically intensive endeavor resulting in a limited database of measurements available to researchers. Drifting or moored buoys capable of measuring sea ice thickness provide an easier method of data collection but also suffer from limited spatial coverage and have not been used in great numbers, although their use has been increasing in recent years (International Arctic Buoy Programme Deployment History, 2007). While unable to measure ice thickness directly, satellite and airborne sensors have been used in the Arctic since the mid to late 1960s to measure sea ice extent, concentration, and freeboard (Nutt, 1963). Using both radar and laser altimeters, satellite and aircraft platforms have collected measurements of ice freeboard, the fraction of total ice thickness extending above the sea surface. Sea ice thickness is then extrapolated from the ice freeboard measurements after adjusting for snow load, and water and ice densities. Because ice freeboard accounts for a relatively small portion (5-20%) of the total ice thickness any errors in determining ice freeboard will lead to even larger errors in the total ice thickness calculations.

In addition to core samples, buoys, and remote sensing methods, ice thickness can be extrapolated from measurements of ice draft - the amount of sea ice below the sea surface. Ice draft measurements are obtained either from submarine or moored Upward Looking Sonar (ULS) systems. Because ice draft constitutes 80-95% of total ice thickness it is considered a more accurate estimate of ice thickness than ice freeboard (Bourke and Garrett, 1987). ULS ice draft data has been collected since the early 1960's when naval submarines began making regular transits under the Arctic sea ice. On occasion, this data has been selectively declassified and made available on a limited basis to scientists and researchers. Within the past ten years an increased effort has been made to declassify more of this data and release it to the scientific community (see Chapter II).

The appeal of using ULS data to gauge ice thickness lies in its extensive datasets (~ 1 m soundings taken over 1000's of kilometers of transit), areal coverage (the portion of the Arctic Ocean that lies outside of Exclusive Economic Zones), temporal range (submarine cruises occurred year-round), and estimated accuracy (± 15-50 cm). Although the submarine cruises were extensive in track length and extended across large portions of the Arctic, they did not occur every year and varied with season and region from year to year. The interpretation of the results obtained from the datasets, consequently, has been open to debate.

Bourke and Garrett (1987) examined ULS ice draft data obtained from 17 U.S. and British submarine cruises spanning the years 1960 to 1982, in addition to airborne laser altimetry data from the U.S. Navy's Birdseye ice reconnaissance flights, and found that mean ice thickness varied from 2.4 m in spring to 3.3 m in summer. The larger summer mean thickness value reflects the absence of thinner first-year ice due to the summer melt season. Seasonal contours of mean ice thickness were developed for the Arctic region north of 65° N and the bi-modal distribution of thin, first-year ice and thick, multi-year ice during winter and spring versus the single multi-year ice signature in summer and fall was noted. From the few cruise tracks that sampled the same region during the same season, no trend in mean ice thickness was found. The overall mean sea ice thickness for the Arctic Ocean was determined to be 2.9 m and the accuracy of ULS ice draft data was estimated to be 0.3-0.5 m when averaged over 50-100 km segments. Bourke and McLaren (1992) analyzed ULS ice draft data from 12 submarine cruises spanning from 1958 to 1987 to further refine seasonal and spatial variability in mean ice draft. In this study the estimated accuracy of ULS derived ice draft data was described as 0.06-0.15 m.

In 1990, Wadhams found evidence of a 15% reduction in mean sea ice thickness between Fram Strait and the North Pole (Wadhams, 1990). The dataset, however, consisted of ULS ice drafts from only two submarine cruises, one in September-October 1976 and the other in May 1987.

McLaren et al., (1992) examined ULS data from six submarine cruises in the vicinity of the North Pole from 1977 to 1990 during the late April/early May time frame and determined that the observed interannual variability of ±1 m was too great to draw definitive conclusions about recent (circa 1992) trends in mean sea ice thickness.

Rothrock et al., (1999) compared ULS ice draft data from six submarine cruises spanning 1958-1976 against three cruises from 1993-1997 and concluded mean ice thickness decreased 42% between the two periods from 3.1 m to 1.8 m.

In 2000 Wadhams and Davis returned to the September-October 1976 dataset from Wadhams’ 1990 study and compared it to a September 1996 submarine cruise that took place in the same general area (Fram Strait to the North Pole) (Wadhams and Davis, 2000). The new study found a 43% reduction in mean sea ice thickness from 4.82 m to 2.74 m and believed the earlier study underestimated the decline in mean ice thickness due to the seasonal mismatch between the 1976 and 1987 cruises. Although both of Wadhams’ studies incorporated cruises that took place largely outside of the area examined by Rothrock et al., (1999), Wadhams and Davis indicated their studies agreed with the results obtained by Rothrock and they supported the conclusion that mean sea ice thickness has declined in the Arctic over the past two decades.

Winsor (2001) re-analyzed the three 1990’s cruises from Rothrock et al., (1999) along with three other cruises from the 1990’s and determined that between 1991 and 1997 mean sea ice thickness remained nearly constant within the study area between the North Pole and Beaufort Sea. Winsor did not support the negative trend in sea ice thickness observed by Rothrock et al., in the 1990s, and when combined with McLaren et al., concluded that sea ice thickness has remained nearly constant at the North Pole from 1986 to 1997.

In 2001, Tucker et al., examined data from nine submarine cruises in the western Arctic along a swath from offshore Alaska to the North Pole (Tucker et al., 2001). The cruises all took place during the spring and spanned the years 1976-1994. Tucker found no trend in mean sea ice thickness at the North Pole, similar to Winsor (2001), and approximately 1.5 m decrease along the southern portions of the swath toward Alaska. Tucker attributed the decrease in western Arctic sea ice during the early 1990’s to the weakening of the wind-driven anticyclonic ice circulation, known as the Beaufort Gyre, in response to a highly positive Arctic Oscillation (AO) index. A weakened Beaufort Gyre results in increased divergence of sea ice leading to an increase in the opening of ice leads (Rigor et al., 2002).

The lower albedo values of open water results in increased solar radiation absorption and consequently increases the summer melt season (Rigor and Wallace, 2004). During winter, the open leads allow for the rapid formation of thin, first year ice resulting in an overall reduction of mean sea ice thickness across the Beaufort Sea. Additionally, a weakened Beaufort Gyre results in decreased convergence of sea ice in the western Arctic and therefore less incidence of ice ridging, less rafting of ice floes, and less recirculation of ice within the Beaufort Sea (Rigor et al., 2002). Furthermore, a positive AO results in an increase in the amount of sea ice being advected out of the Arctic Ocean through Fram Strait. Tucker et al. (2001), attributed the reduction of sea ice thickness in the Western Arctic to the effects of the positive AO regime observed in the 1990's while noting that the North Pole remains in an strongly advective regime during both phases of the AO and hence observes little change in mean sea ice thickness.

In 2002 Holloway and Sou utilized model results to re-examine ULS derived ice thickness studies by Rothrock et al. (1999), Wadhams and Davis (2000), Winsor (2001), and Tucker et al. (2001) and concluded that ice thickness has decreased to a lesser extent than previously reported – 16-25% from 1987 to 1997 (Holloway and Sou, 2002). The large and rapid declines found in studies by Rothrock et al., and Wadhams and Davis were a result of overestimation due to spatial and temporal undersampling. Holloway and Sou found no linear trend in sea ice volume over the past 50 years and attributed perceived sea ice losses due to wind advection and redistribution from the areas sampled by submarine cruises to other regions.

Laxon et al., (2003) stressed the need for knowledge of the natural variability of Arctic sea ice thickness in order to accurately validate global climate models. They note that the datasets of observed sea ice thickness are not extensive enough to provide an accurate assessment of the state of ice thickness in the Arctic. From an examination of the observed annual variability of Arctic ice mass from 1993 to 2001 they find an observed variability 50% greater than predicted by model simulations. They also found that ice mass can change by up to 16% within a year and that this variability must be taken into account when trying to determine trends in sea ice thickness from submarine ice draft measurements.

The studies described above draw different conclusions from the same ULS ice draft datasets. Some studies indicated significant declines in sea ice thickness while other studies described how interannual variability or sea ice advection can lead to overestimation of ice thickness losses. One thing is clear however, by sampling only a limited number of submarine cruise tracks it is difficult to make definitive conclusions on the state of sea ice thickness. A shift of one year earlier or one year later in the cruises utilized in a particular study can lead to significantly different results (Holloway and Sou, 2002).

Because of the sparseness of sea ice thickness measurements, numerical models are heavily relied upon to estimate the state of Arctic sea ice (Laxon et al., 2003). It is therefore necessary to determine the accuracy of Arctic Ocean models with respect to their ability to depict sea ice thickness if accurate predictions of future sea ice trends are to be made. McNamara (2006) compared ULS ice draft data from 19 submarine cruises spanning from 1986 to 1999 against the NPS 1/12 degree pan-Arctic coupled ice-ocean model (Maslowski et al., 2004) to assess model skill. The current study attempts to further validate the NPS model with additional ULS ice draft data.

C. NAVY RELEVANCE

Until the recent decline in Arctic sea ice, the United States' national security concerns in the Arctic focused on tracking enemy aircraft and submarine operations and countering the ballistic missile threat. The responsibility of protecting the nation and its interests in this region was primarily shared between the U.S. Air Force and the U.S. Navy. Above surface responsibilities were the purview of the Air Force which operated its assets to counter the airborne and ballistic missile threat, while below surface responsibilities were assigned to the Navy which operated its fleet of ballistic and fast-attack submarines to provide nuclear deterrence and counter the enemy submarine and ballistic missile threat. The U.S. Coast Guard also operated in the Arctic region, mainly in the ice free portions of the Bering Sea and along the northern coast of Alaska, but its main focus was on safety of life and patrol of U.S. fisheries.

Because most of the Arctic Ocean has been covered with sea ice year-round, the few numbers of surface vessels that regularly operate in these waters have mainly been scientific or exploratory in nature. What little commercial shipping activity existed was confined to seasonal ice-free zones along the coastline and military surface ship patrols have been very limited. However, the status quo will not hold in the future. As the Arctic sea ice continues to decline in thickness and extent as forecasted (IPCC, 2007: Summary for Policymakers), increasing portions of the Arctic will become ice-free on a seasonal basis. This development will have vast implications for the region in general and for the countries that border the Arctic Ocean.

A seasonally ice-free Arctic Ocean is not even a reality yet and changes can already be seen in the political arena. Countries such as Russia and Canada have quickly moved to expand or strengthen their claims to territorial waters and Exclusive Economic Zones (EEZ) by extending the reach of their continental shelves. In early August 2007, Russia planted a flag on a section of the Lomonosov Ridge under the North Pole claiming it was an extension of the Russian continental shelf and thus by legal definition vastly expanding its EEZ. For many years Canada has maintained that the Northwest Passage through the Canadian Archipelago is part of its internal waters while the U.S. and other nations consider the route through the archipelago part of an international strait and thus open to transit passage by sovereign nations. Beginning in 2006, as part of its stepped up legal claim to the Northwest Passage, Canada has officially stopped referring to the Northwest Passage by name and has started referring to it as part of the Canadian Internal Waters (VanderKlippe, 2006). Meanwhile an ongoing dispute between the U.S. and Canada over the EEZ boundary in the Beaufort Sea between Alaska and the Yukon Territory remains unresolved even as each country conducts oil and mineral explorations in the disputed territory (Lemieux, 2007).

The changing conditions in the Arctic Ocean are of significant importance to the national security interests of the United States spanning across several areas of concern including: national defense, territorial integrity, freedom of navigation, commerce, energy resources, environmental protection, and search and rescue operations. Although the wide-ranging implications of diminishing sea ice will affect multiple federal agencies, the greatest impact will be felt by the U.S. Navy as it reshapes its strategies and policies to adjust to the changing physical and political environment.

Since the start of the Cold War, the Arctic Ocean has been a quiet battleground between the U.S. and Russia with each country's navy operating ballistic and fast-attack submarines under the ice cap. From the naval perspective, the diminishing Arctic sea ice will have significant implications for both the physical and operational environment in which the Navy currently operates.

Physical changes include a shift in the salinity of the Arctic Ocean toward a less saline regime as freshwater influx increases due to melting sea ice and freshwater runoff from rivers and streams increases due to thawing permafrost. The thawing permafrost will also increase the amount of sediment added to the Arctic Ocean from river runoff and coastal erosion which will reduce water clarity and alter water chemistry. Warming surface waters and decreased salinity will affect the acoustic propagation properties of the Arctic Ocean and the reduction in sea ice will alter ambient noise levels by exposing more of the sea surface to the effects of wind, wind driven waves, and precipitation. Weather patterns in the Arctic and sub-Arctic are also expected to change with a warming Arctic. A warmer and more moist boundary layer will lead to increased cloud cover and precipitation, leading to increased episodes of ship and aircraft icing and reduced visibilities. Polar lows are expected to become both more frequent as storm tracks shift northward and stronger with the increase in available latent energy due to the warming Arctic and sub-Arctic.

From an operational perspective the Navy can expect to see an increase in the amount of surface vessels, both commercial and military, in the region as the diminishing sea ice opens up sea lanes and operating areas. Consequently, the Navy in conjunction with the Coast Guard will need to begin patrolling the Arctic Ocean in response to the increased presence of foreign vessels. The Navy’s surface fleet does not have much, if any, experience operating in Arctic waters. Other than icebreakers, U.S. naval vessels are not designed or built for operation in seasonally ice-covered waters and surface naval crews do not have extensive experience in maneuvering through ice fields or coping with superstructure icing and freezing sea spray.

The U.S. submarine fleet, however, does have considerable experience in Arctic operations but this knowledge will have to adjust to the changing physical conditions including an altered acoustic environment. As mentioned previously, the warming of the surface waters and changes in salinity will affect sound propagation which in turn will affect sonar performance and tactics. Currently, the central icepack provides a dampening of surface driven ambient noise. As the icepack melts and breaks apart, ambient noise will increase throughout the Arctic to the levels currently only seen at the marginal ice zones where melting ice is actively grinding and colliding with other floes. The acoustic environment will see more variety on a seasonal basis as the decline in the Arctic icepack accelerates. Summer months will see less ice-generated noise but an increase in ambient noise due to wind-driven surface waves and precipitation. As the amount of open water in the Arctic increases each summer, the Arctic icepack will become increasingly dominated by thin, first-year ice with the onset of fall and winter rather than the thick, multi-year ice that normally characterizes the icepack. Thin, first-year ice is more susceptible to advection, deformation, ridging, and rafting and will thus increase the levels of ice-generated noise in the Arctic from fall through spring. From a tactical perspective, ice keels extending under the Arctic icepack have provided cover to stationary submarines by masking and deflecting sonar signals. As sea ice melts and ice keels decrease in size and extent, submarines will find it harder to take advantage of these masking properties. The changing conditions will make submarine operations more hazardous as submarines will find it more difficult to take advantage of the icepack to remain hidden and will find themselves operating in more actively dynamic environments as shifting ice floes and increased surface vessel traffic impacts the region.

The opening up of the Arctic Ocean to commercial and military vessels will see the need for a new class of naval vessels specifically designed for operations in the seasonally ice-free Arctic. As mentioned earlier, the current fleet of Navy surface vessels are not designed or built for Arctic operations. As conditions in the Arctic outpace ship procurement programs, the Navy's surface fleet can conceivably be called upon to begin Arctic patrols with existing assets. The harsh environmental conditions will make operating the current class of vessels, aircraft, and weapon systems challenging due to increased safety concerns from maneuvering through the icepack, difficulties with operating under extreme cold air and sea surface temperatures, difficulty in maintenance and upkeep of equipment, and the near complete lack of infrastructure to support a northern fleet. In addition, the diversion of existing naval assets to the Arctic will come at the expense of the Navy's fleets currently engaged and positioned in other parts of the world. The necessity of a new class of naval vessels specifically built for Arctic operations, along with the infrastructure required to support them will become vital if the U.S. is to safeguard its interests in the Arctic. Due to extended amount of time required to appropriate funding, design, test, build, and field new vessels and equipment and in light of the accelerated declining trend in Arctic sea ice, the U.S. needs to begin preparing now for a seasonally ice-free Arctic.

The Navy has a long and successful history of enforcing the U.S.'s commitment to the freedom of the seas by transiting through contested waters. Although often seen as a secondary or peripheral role of the Navy, this practice helps set legal precedent for the right of international navigation and denies the viability of contested claims. As navigable transit lanes open up along the Northwest Passage through the Canadian Archipelago and the Northern Sea Route (NSR) along Russia's northern marginal seas, commercial shipping traffic will only continue to increase as international companies try to take advantage of the shorter distance (and hence time and cost) of transporting commercial goods between Asia and Europe. It is in the U.S. interest to ensure the continued free navigation of the Arctic Ocean for both commercial and military vessels. The importance of the Navy's frequent and pervasive presence in the Arctic will only continue to increase as the navigable waters of the Arctic Ocean open up as the sea ice cover diminishes.

The U.S. is not immune to the lure of expanded opportunities as the Arctic environment becomes more hospitable to commercial enterprises. All of the nations bordering the Arctic Ocean – Canada, Russia, Denmark, Norway, Sweden, Finland, Iceland and the U.S. – as well as other, yet to be determined, non-Arctic nations can be expected to aggressively seek to take advantage of the opening up of the Arctic Ocean for oil and gas exploration, mineral resources and seabed mining, and new fishing grounds. The U.S. interest in claiming rights to its own natural resources within its territorial waters and protecting against encroachment from foreign competitors requires a strong naval presence in this new, dynamic frontier. In addition to the Navy's increased presence in the Arctic region, the U.S. Coast Guard will also see its role in territorial waters protection, law enforcement, search and rescue, fisheries management, and environmental protection, increase in importance as the territorial waters north of Alaska see an increase in commercial activity.

A warming Arctic Ocean will not only have regional impacts for the Navy but also affect naval operations world-wide. Global warming and climate change will lead to increased instability throughout the world as nations compete for resources. Climate change will affect food and water supplies and production, increase the dangers of health pandemics, destabilize and uproot populations due to changes in resource availability, increase severe weather events, lead to the loss of shorelines due to rising sea levels, and increase geopolitical tensions worldwide as countries attempt to adapt to a changing world. The Navy will find itself in an increasing unpredictable geopolitical environment and will be called upon to respond to growing political and humanitarian crises. Global climate change will affect the Navy in all aspects of operations, not only with respect to the Arctic.

In order to properly plan for future challenges and adjust strategies and policies the U.S. Navy will need to have a reliable and accurate assessment of both the rate and extent of the forecasted changes to the Arctic Ocean's icepack. Computer models that can accurately model sea ice conditions as they existed in previous years can then be employed with high confidence when projecting future changes to sea ice thickness and coverage. This study provides an assessment on the performance over a 22-year span (1979-2000) of the NPS 1/12 degree pan-Arctic coupled ice-ocean model in comparison to observed sea ice draft data.

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II. DATA AND MODEL DESCRIPTION

A. DESCRIPTION OF SUBMARINE UPWARD LOOKING SONAR DATA

In June 2006, the National Snow and Ice Data Center in Boulder, Colorado released fifteen new Upward Looking Sonar (ULS) datasets to compliment the existing 22 datasets on file at its public website. The new ULS data was prepared by the Polar Science Center at the Applied Physics Laboratory, University of Washington and was derived by digitizing analog ice draft measurements originally recorded on rolls of paper traces (Wensnahan et al., 2007). Of the fifteen datasets two were from years prior to 1979 (the first operational year of the NPS model) leaving thirteen new ULS datasets available for comparison with the NPS ice-ocean model.

The ULS ice draft measurements in this study were made by U.S. Navy submarines using upward looking, narrow beam sonar arrays. The sonar measured the distance from the submarine's sonar assembly to the bottom-side of the sea ice as the submarine transited along path. This measurement yields sea ice draft – the portion of the sea ice below the sea surface. In processing the data, APL corrected for depth errors, removed erroneous drafts, and spatially interpolated data to maintain consistent measurements at approximately 1 m intervals along track.

The data were divided into straight-line (great circle) segments of up to 50 km in length. Some segments were shorter than 50 km in cases where data dropouts were in excess of 0.25 km or if the submarine changed course or depth. The U.S. Navy's guidelines for the release of the previously classified, ULS ice draft measurements stipulated that data positions were to be rounded to the nearest 5 minutes of latitude and longitude and transit dates were to be rounded to the nearest third of the month. The degradation in the location and date of the ice draft data is not considered significant for this study since the NPS model output consists of monthly mean ice thickness values within 9 km x 9 km grid cells.

The original release of the previously classified data in 1997 was confined to what has been termed the "Gore Box" in recognition of then Vice President Gore's initiative to provide the data to the international scientific community. The U.S. Navy subsequently expanded the box to its present dimensions (Figure 1.). The thirteen new ULS datasets used in this study were confined within the "current release area" (Figure 2.).

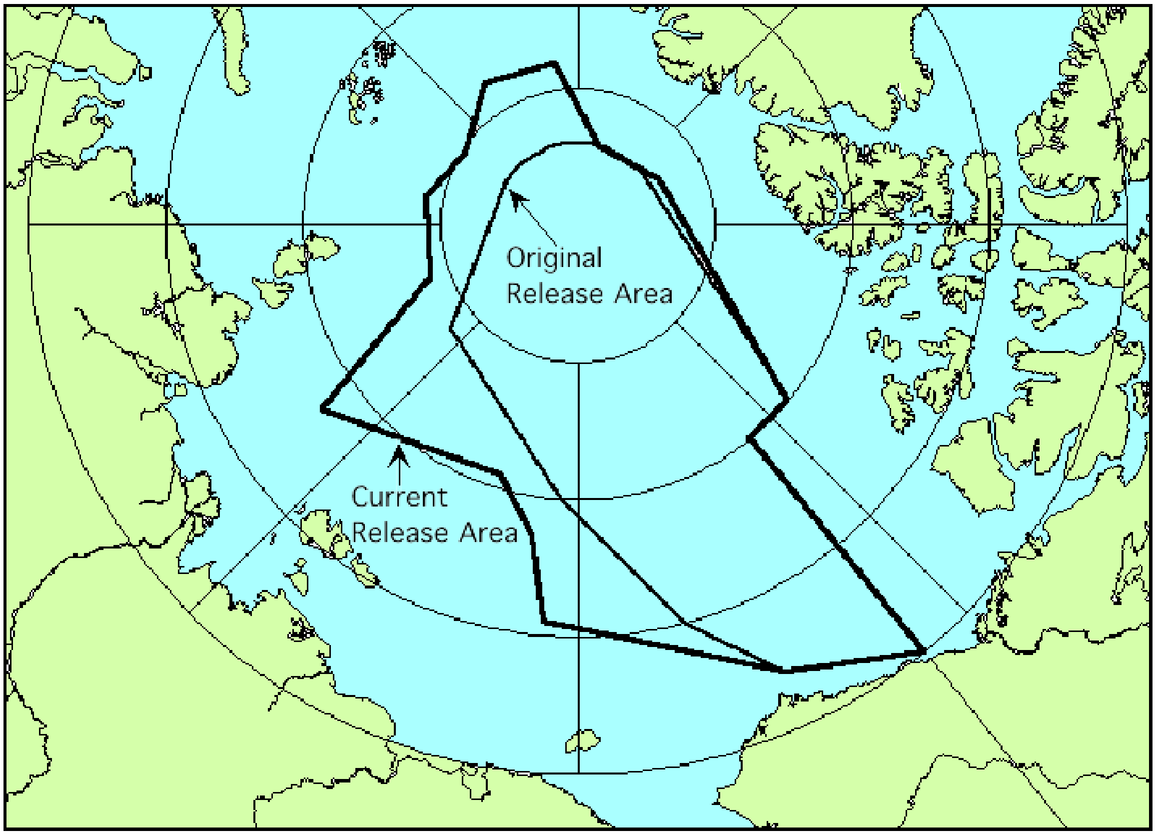

Figure 1. Original “Gore Box” and current expanded release area [From NSIDC, 2007].

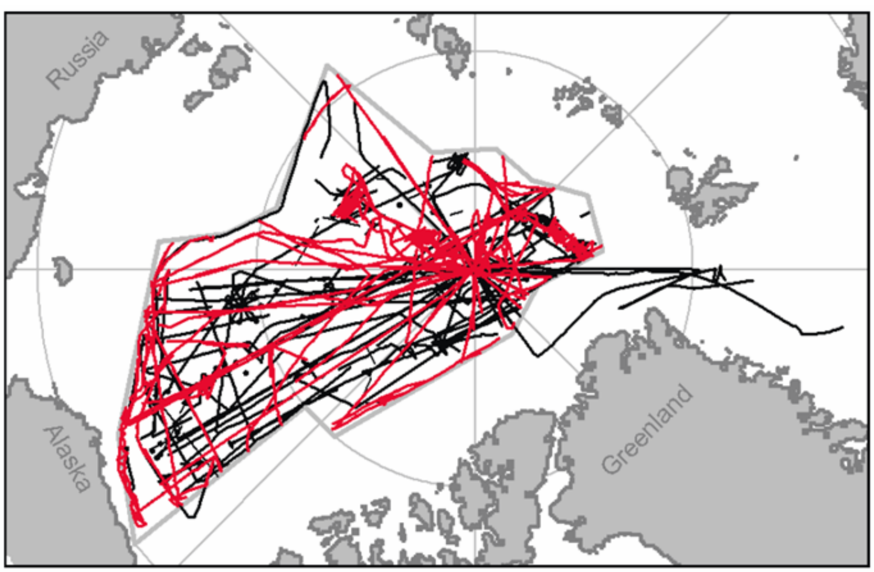

Figure 2. Newest NSIDC submarine ULS datasets – 2006 release shown in red [From Wensnahan et al., 2007].

B. DESCRIPTION OF NPS 1/12 DEGREE PAN-ARCTIC COUPLED ICE-OCEAN MODEL

The NPS model domain (Figure 3.) covers all Northern Hemisphere seasonally ice-covered seas including the Sea of Japan, the Sea of Okhotsk, the sub-Arctic North Pacific and North Atlantic Oceans, the Arctic Ocean, the Canadian Arctic Archipelago, and the Nordic Seas and also includes all major inflow and outflow areas of the Arctic Ocean. The model is configured on a 1/12° (approx 9 km), rotated spherical coordinate grid in the horizontal plane and is divided into 45 fixed z-levels in the vertical plane. Model bathymetry north of 64° N is based on 2.5 km resolution International Bathymetric Chart of the Arctic Ocean digital bathymetry dataset (Maslowski et al., 2004).

The model was started from rest and went through a 48 year spin-up process resulting in 1979 being the first operational year of the model. Due to the large size of the model domain and storage limits, monthly-mean model output was saved, including ice thickness values which were used to compare with submarine ULS datasets from 1979 to 2000. Atmospheric forcing from the European Centre for Medium-range Weather Forecasts (ECMWF) consisting of 10 m wind (*u* and *v*) velocity components, surface pressure, temperature, dew point, and incoming long-wave and short-wave radiation, was interpolated onto the model grid. The region of interest for this study is located exclusively within the Arctic Ocean and therefore model boundary effects were not considered a significant factor (Maslowski et al., 2004).

For additional information on the NPS model characteristics refer to Marble (2001), Maslowski and Lipscomb (2003), and Maslowski et al., (2004).

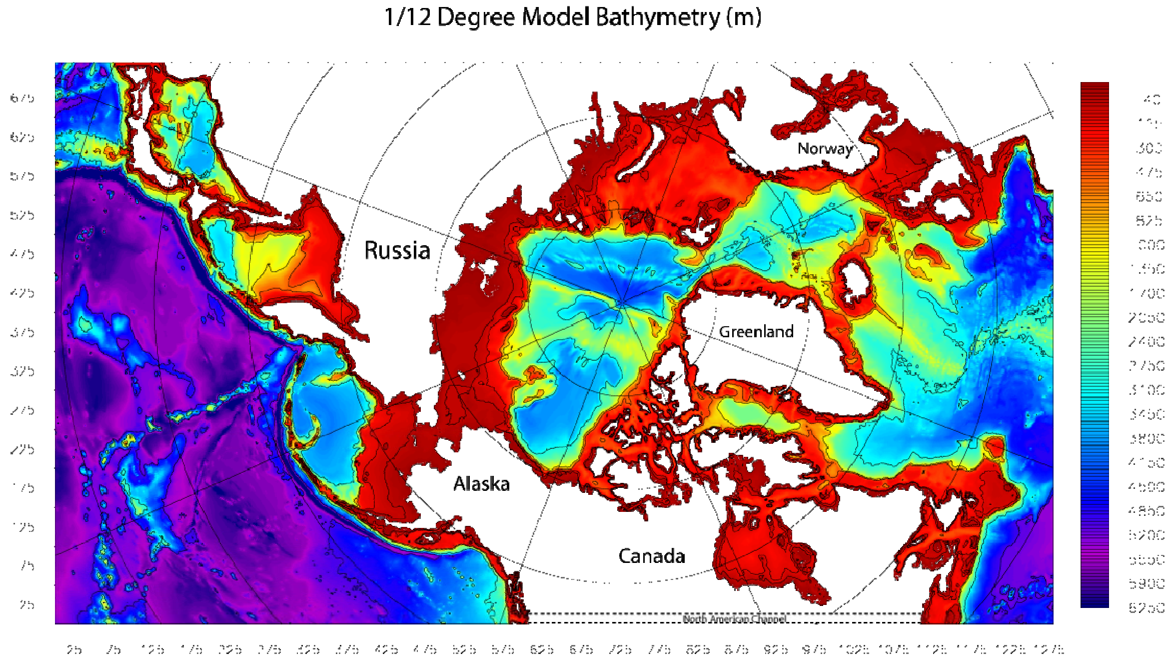

Figure 3. NPS model domain and bathymetry. Two dashed lines across Canada indicate the location of an artificial channel connecting the North Atlantic with the North Pacific to balance the net northward water transport through Bering Strait. [From Maslowski et al., 2004].

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III. METHODOLOGY OF ANALYSIS

A. ANALYSIS METHOD

The major difficulty with comparing ULS ice draft measurements against the NPS model's monthly mean ice thickness output is that the two datasets are not compatible in their spatial or temporal characteristics. The ULS data were gathered along a straight line submarine transit with ice draft recordings made approximately every meter while enroute. This method yields a wealth of data points, on the order of hundreds of thousands of draft measurements for each cruise. For security reasons the data was not specified by date, but was divided and grouped to the nearest third of the month. The NPS model, on the other hand, provides monthly, mean ice thickness measurements centered on a 9 km by 9 km grid. Consequently, the dataset of model ice thickness output is several orders of magnitude less than the ULS draft datasets.

The difference in time scales between the two datasets was not considered significant as a monthly division of the data is the current standard practice throughout the literature and any revealed differences would most likely be minimal.

The difference in the two datasets' spatial scales, however, was considered significant and had to be reconciled in order to perform a reasonable comparison between the two datasets. The method of analysis used to compare the ULS draft datasets with NPS model output is the same as developed by McNamara (2006) and is described in the following paragraphs.

1. Data

The data for each submarine cruise was divided into approximately 50 km segments by APL based on a straight line (great circle) transit at constant depth and course. In order to compare ULS ice draft measurements to model ice thickness values it was first necessary to convert the ULS ice draft data to equivalent ice thickness values. This was done by applying a correction factor of 1.12 to each ice draft measurement, as per Rothrock et al., (1999), thus converting the ULS ice draft data to ULS ice thickness values.

Because draft measurements were recorded every meter during transit there were literally thousands of draft measurements available per cruise segment. In order to realistically manage this large amount of data, a mean thickness was calculated as a representative value for each cruise segment. Within each cruise, however, segment lengths varied significantly (in one case segments varied between 3.962 km and 402.979 km). A weighted mean based on overall cruise length was therefore calculated for each segment, placing greater emphasis on longer segments over shorter segments. In addition to the mean weighted thickness, the standard deviation of each segment was also computed. The weighted means and standard deviations for each cruise segment were then combined to yield an overall mean ice thickness and standard deviation for each cruise.

2. Model

The NPS model outputs sea ice thickness as a monthly mean value centered on each 9 km by 9 km grid cell. In order to increase the number of model output points being used for comparison, McNamara (2006) used a three cell wide swath, which included the cell that covered the cruise track and the adjacent cells to either side of the central cell, to compute a weighted mean thickness for each cruise segment. The model output per segment was then combined to yield an overall cruise ice thickness mean. This same method of analysis was conducted in this study. As with the ULS data, the model's standard deviation was computed for each segment and the overall cruise. Some of the cruises in this study covered a two month period which required the model ice thickness output to be computed for the corresponding month and then combined to reach an overall thickness value for the entire cruise.

3. Probability Density Functions (PDF)

Once mean weighted ice thickness values for the ULS data and NPS model output were calculated for each segment, the data were then binned into 10 cm ice thickness bins and plotted together as a PDF with y-axis values representing a percentage of points with a given ice thickness relative to the total number of points in a cruise. Detailed discussion and comparison of the data and model PDFs for each of the thirteen cruises in this study are discussed in Chapter IV.

B. RELIABILITY OF METHODS

The submarine derived ice draft data used in this study was obtained using time tested, proven technology, i.e. upward looking sonar arrays and depth gauges. The data was not gathered using experimental or unproven technology. The accuracy of ULS and depth gauge derived ice draft data ranges from 6-15 cm (Bourke and McLaren, 1992) to 30-50 cm (Bourke and Garrett, 1987). After a detailed examination of the errors associated with the collection of ULS derived ice drafts by U.S. Navy submarines, Rothrock and Wensnahan (2007) determined the accuracy to be 25 cm. Because ice draft - the amount of total ice thickness that lies below the sea surface - represents such a large portion of the total ice thickness (~ 80-95%), the ice draft measurements are a reliable indicator of total ice thickness (Bourke and Garrett, 1987). By applying a correction factor of 1.12 to the ice draft measurements total ice thickness was then reliably extrapolated from the ULS ice draft datasets. Although the use of a constant correction factor may neglect to account for localized variations in snow load and seawater and ice densities, these variations are considered to be minimal due to the overwhelming contribution of ice draft to the total ice thickness. As uncertainties in the ULS ice draft measurements range between 25 cm (Rothrock and Wensnahan, 2007) and 30-50 cm (Bourke and Garrett, 1987), 30 cm can be considered a reasonable estimate of ULS ice draft measurement error. Keeping in mind that ice draft makes up 80-90% of the sea ice thickness measurement, the uncertainty in the ice thickness calculations with a 30 cm ULS draft measurement error can range from 28 cm to 36 cm.

IV. DISCUSSION OF RESULTS

A. DESCRIPTION OF COMPARISON RESULTS

The Probability Density Functions of submarine ULS observations vs. NPS model output are displayed in the following section. Weighted, mean sea ice thickness observations from ULS derived data are depicted in red and NPS model output is indicated in blue. The x-axis of the PDF is divided into 10 cm bins, while the y-axis indicates the percentage of ice thickness measurements that fall within a particular bin relative to the total number of measurements (or model points). To the left of the PDF in each figure is a graphic of the cruise track for that particular cruise. The graphics for each cruise were obtained from NSIDC's website: http://nsidc.org/data/docs/noaa/g01360_upward_looking_sonar/index.html (August, 2007). Below each cruise track are three ice thickness values: h_{obs} refers to the weighted, mean ULS ice thickness in meters for that cruise; h_{model} refers to the weighted mean model ice thickness in meters; and Δh indicates the ice thickness difference in centimeters between the mean observed and the NPS model. Further statistics for each cruise are listed in Table 1. For purposes of this study "ice ridging" and "ice rafting" are used interchangeably as the exact phenomenon was not discernable without a more detailed analysis and the conclusions reached in the comparisons are the same for either case.

B. SEASONAL COMPARISON

The thirteen submarine ULS vs. NPS model comparisons were first grouped according to the month in which the submarine cruise took place to see if there were any differences in how the model handled different seasonal conditions. For this comparison the datasets were divided into spring (April-June), summer (August-September), and fall (October-November).

1. Spring

The first feature to observe in the four spring data samples is that the sea ice PDFs consist of thick multi-year ice with no signature of thinner, first-year ice. This is in direct contrast to the observations of Bourke and Garrett (1986) who saw thinner mean sea ice thickness in winter and spring due to the presence of large amounts of first-year ice. The datasets for April through May all show thicker mean ice thickness measurements than seen in the summer or fall datasets, (with the exception of August 1983, near the Canadian Archipelago where ice fields are convergent) and ice thickness values of less than 3.0 m are not seen. The data from May-June 1983 do show a few ice thickness values less than 3.0 m, most likely due to the beginning of the summer melt in the latter half of the cruise.

The NPS model performed well in representing the single mode nature of the multi-year ice during the spring but frequently had difficulty adequately depicting either the existence or the observed amount of pressure ridges.

The model’s best performance in spring was seen during the April-May cruise of 1988 as seen in Figure 4. .

Although the mean weighted thickness in the model is slightly less than the data thickness, the range and percentages of the model PDF distribution are very similar to the observed data.

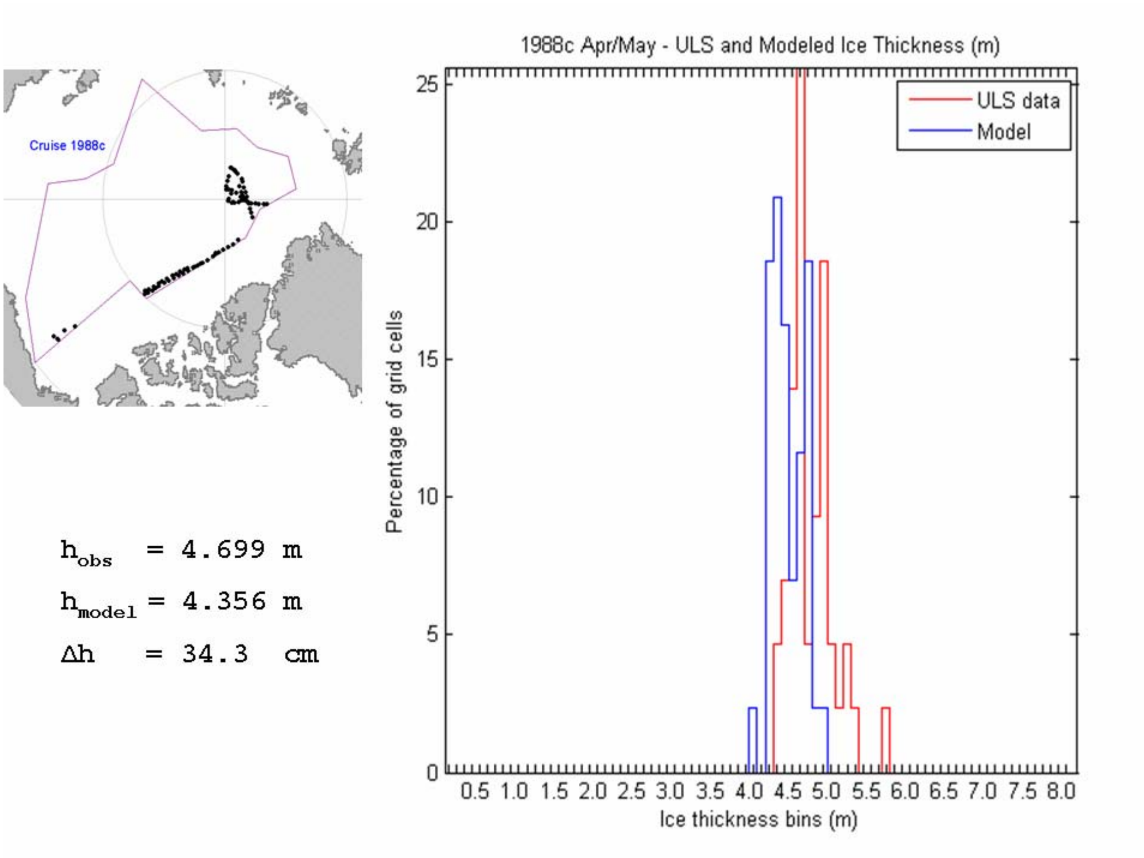

Figure 4. April-May 1988 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

Figure 5. shows the case where the model did not accurately depict the pressure ridges, or ice rafting, observed in the data. The model's performance in April 1979 does indicate an attempt at depicting the existence of the ridges by the nature of the dual peaks in the PDF but the model's thicker peak (right-hand side) is neither thick enough nor extensive enough in range. It was noted that

throughout the study the model did not depict ice thickness bins in excess of 5 m. Ice ridging and rafting typically occur on spatial scales much less than the 9 km by 9 km grid cell of the model and, unless the ridging is extensive, any attempt by the model at depicting ridging is often washed out in the final mean calculation by the preponderance of the non-ridged ice within the remainder of the grid cell.

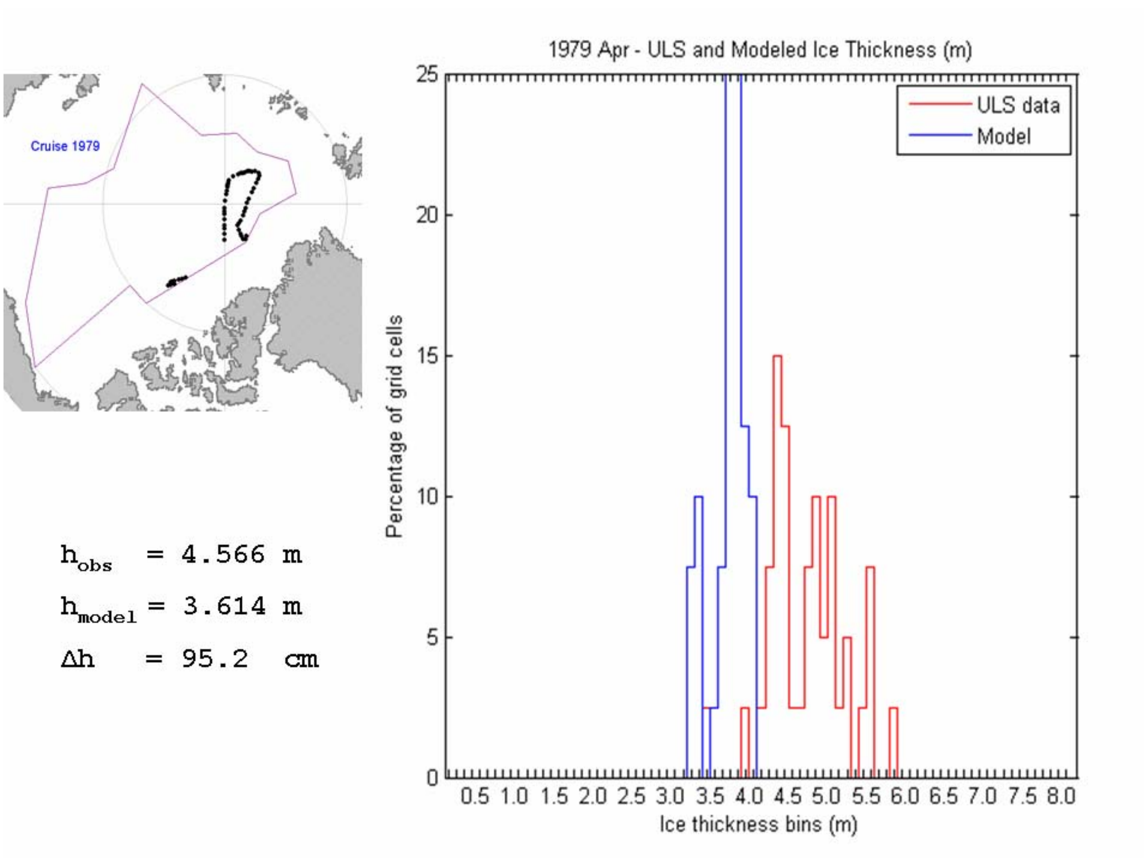

Figure 5. April 1979 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

During the April 1993 cruise (Figure 6. Figure 6.) the model’s mean ice thickness was 40 cm thicker than the observed data; a uncommon case where the model overestimated sea ice thickness. Both the model and data, however, indicated minimal rafting during this cruise.

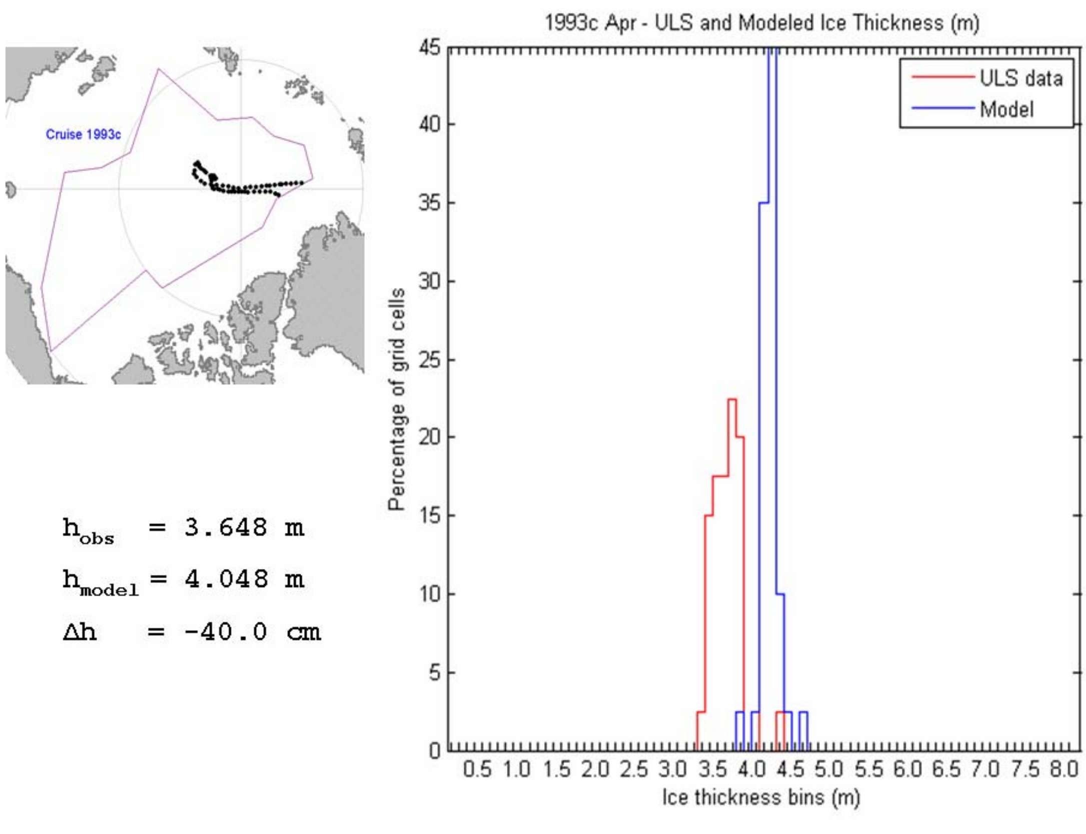

Figure 6. April 1993 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

In the May-June cruise of 1987 the model again did not perform well with respect to predicting the existence and amount of ice rafting. Additionally, the model did not depict the existence of a small fraction of thinner ice, whose presence was most likely due to the beginning of the summer melt (Figure 7.). The failure to depict the thinner ice may simply indicate a timing issue with the model's onset of the summer melt or with the model's inability to represent an open water fraction while predicting only mean ice thickness per grid cell. Unfortunately, with the exception of the 1987 cruise which extended into June, there are no datasets available in any year from NSIDC during June and July to investigate the timing issue further.

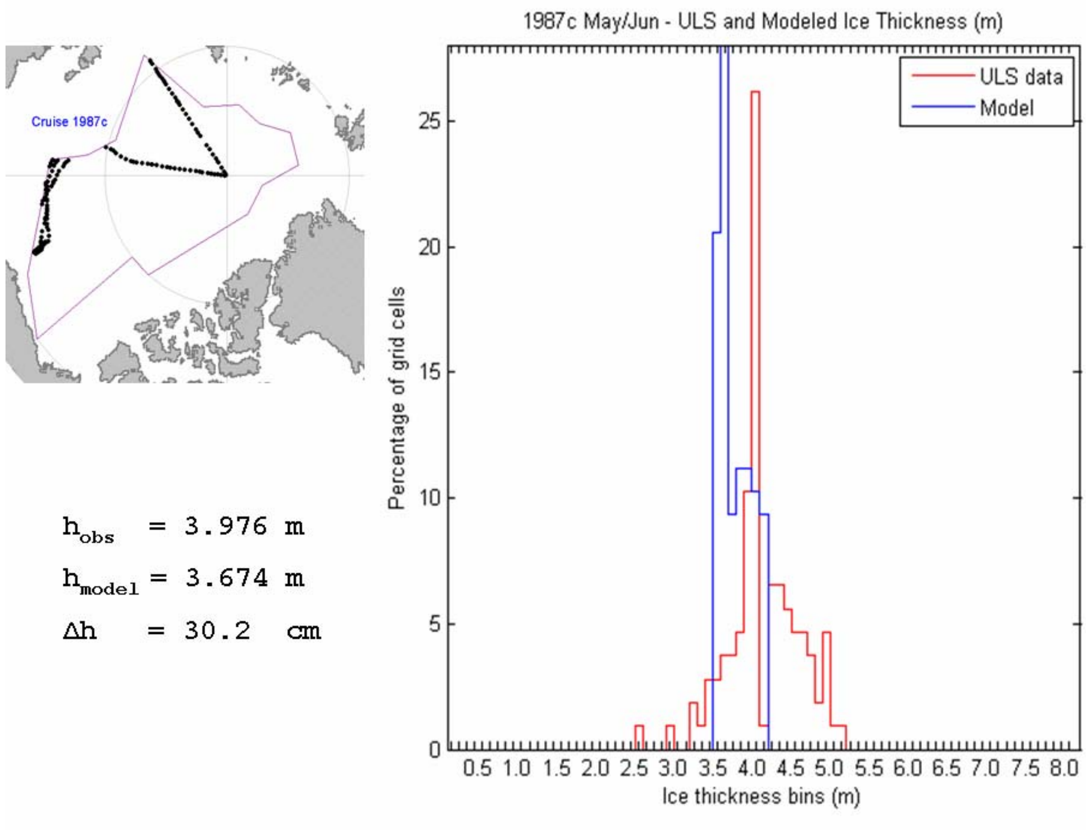

Figure 7. May-June 1987 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

2. Summer

During the summer cruises, the model performed reasonably well in one instance but ice rafting continued to be an issue for the model. In addition, it was noticed that the model showed significant weaknesses in its ability to represent melting ice.

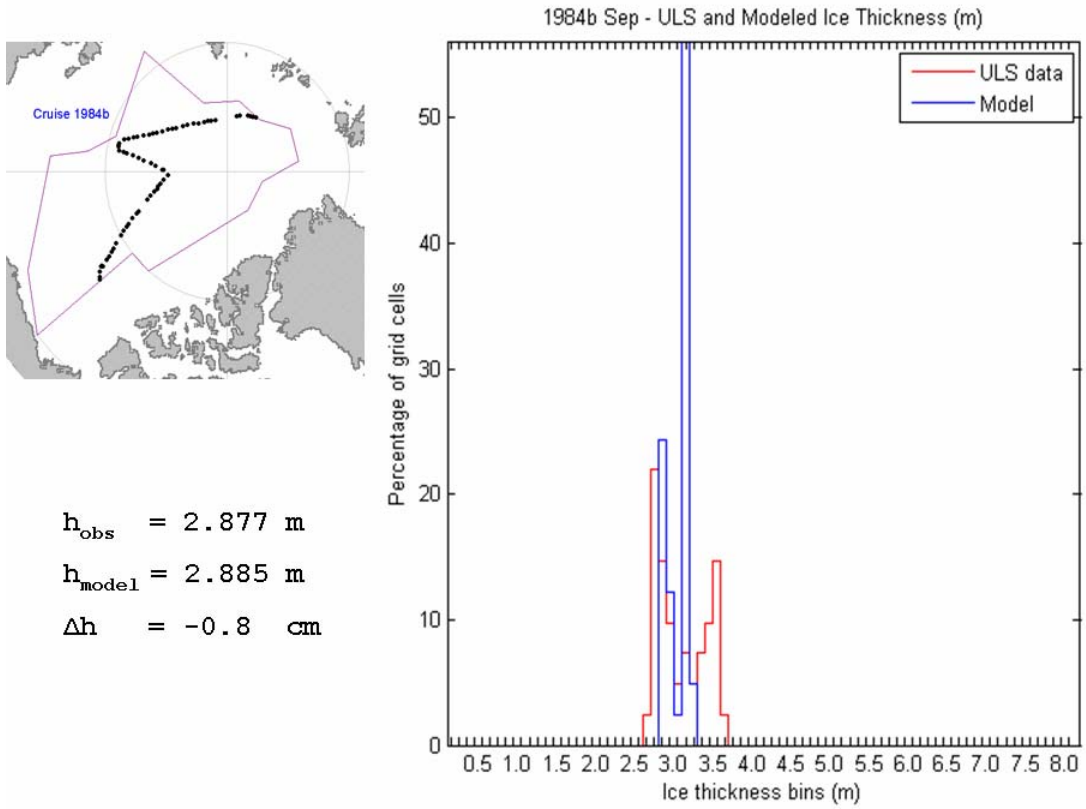

Figure 8. September 1984 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

As seen in Figure 8. Figure 8. , the model performed reasonably well with comparison to the data in the September 1984 cruise but ice rafting continues to be an issue for the model. The model represented the thinner data peak centered around 2.75 m reasonably well, but was approximately 25 cm too thin on the thicker 3.5 m peak. Despite not showing the true nature of the ULS data distribution, the mean ice thickness comparison is only 8 mm different! This result appears extremely good from a pure comparison of weighted means but if the distribution of thin ice versus thick ice is important for a model’s ability to account for ice advection or perform heat budget calculations it is misleading.

The weakness in the model’s ability to accurately depict ice rafting is most noticeable in the August 1983 cruise, as seen in Figure 9. . In this case the model PDF centers over 50% of the ice thickness values around approximately 3.3 m with a few thicker values up to 4.0 m. Significant and discreet ice rafting, however, is observed throughout the ULS data extending up to 6.75 m in thickness. As mentioned previously, the model’s tendency to wash-out any ridging is the likely cause of the absence of ridging in Figure 9. .

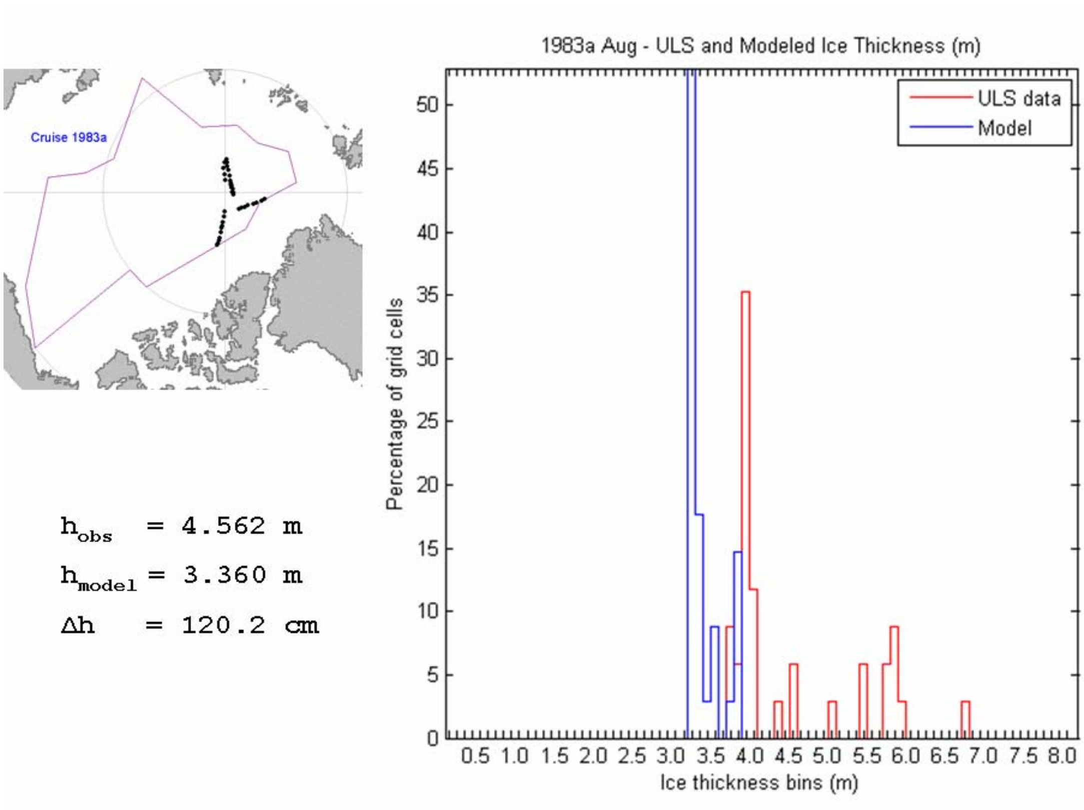

Figure 9. August 1983 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

In the remaining two summer datasets, the inability of the model to depict the existence of melting ice was the primary issue. The September 1990 cruise, Figure 10. , shows the best example of this event. The data from this cruise reveals a dual mode PDF with thicker multi-year ice and thinner, melting ice. The model, however, only depicts the thicker, multi-year ice and shows this in greater percentages and thickness than what is indicated by the data for the multi-year ice. Further analysis of the model is needed to determine if accurately depicting melting ice is a matter of timing. The September 1994 cruise, Figure 11. , shows a similar issue, however this cruise was relatively short hence some of the mismatch could be due to comparison of model monthly mean values. Future analyses could re-examine this cruise by attempting comparison of daily model ice thickness values if model temporal resolution increase to this degree.

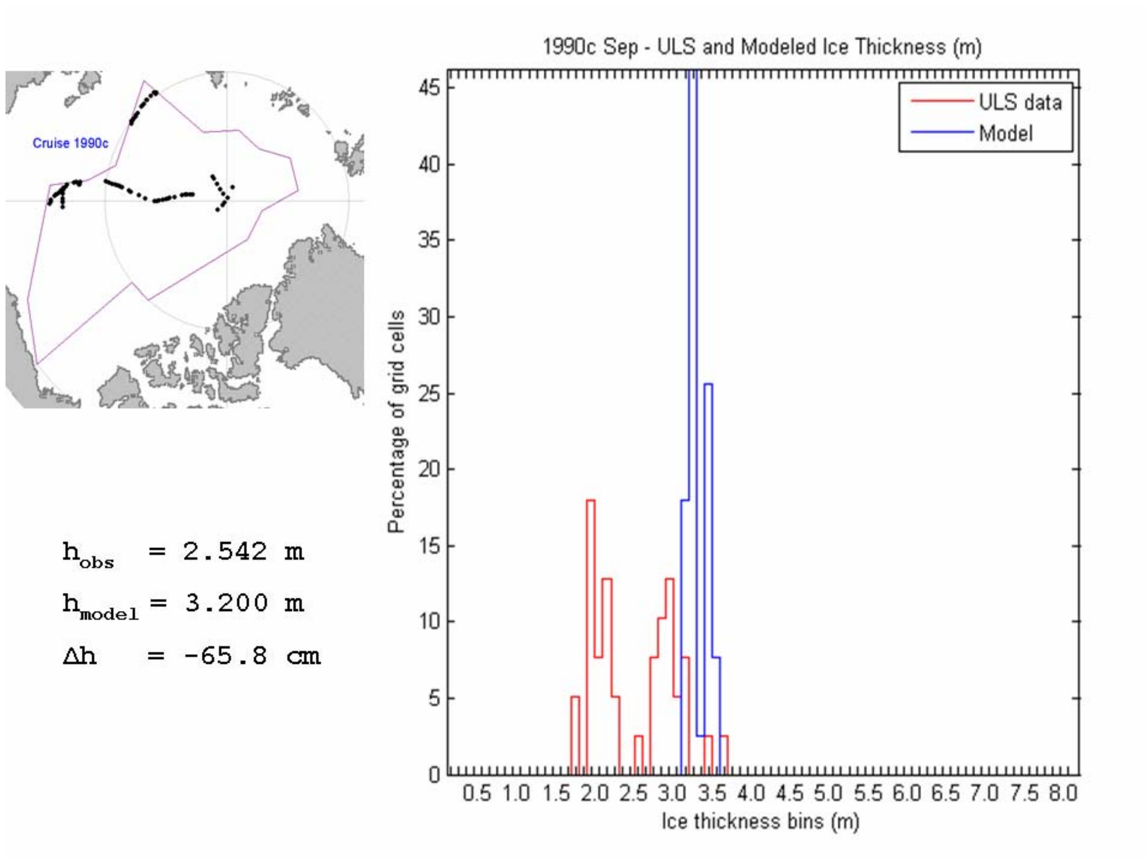

Figure 10. September 1990 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

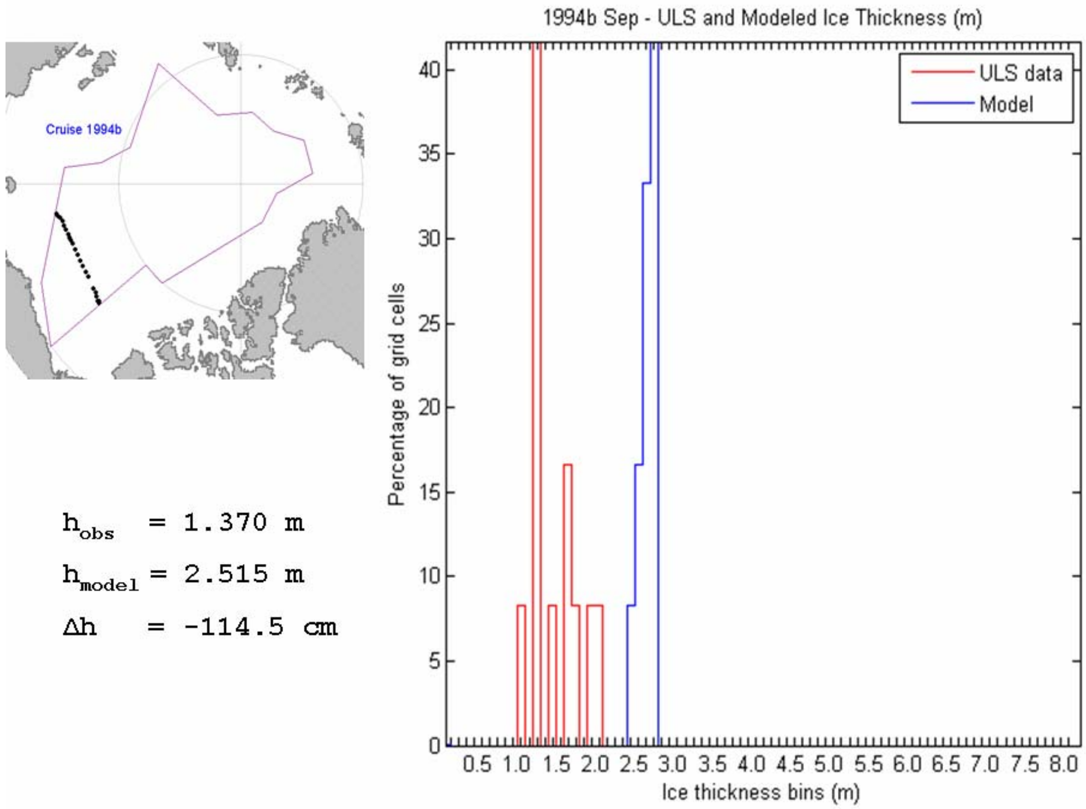

Figure 11. September 1994 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

3. Fall

Model performance in the fall months continued to suffer from the inability to depict the existence of ice ridging or rafting. In cases where the model showed the existence of ridging it was typically up to 1.5 m too thin. In addition, the model was seen to have difficulties depicting the thinner newly forming, first-year ice. The model's best performance in the fall can be seen in the October 2000 cruise, Figure 12.

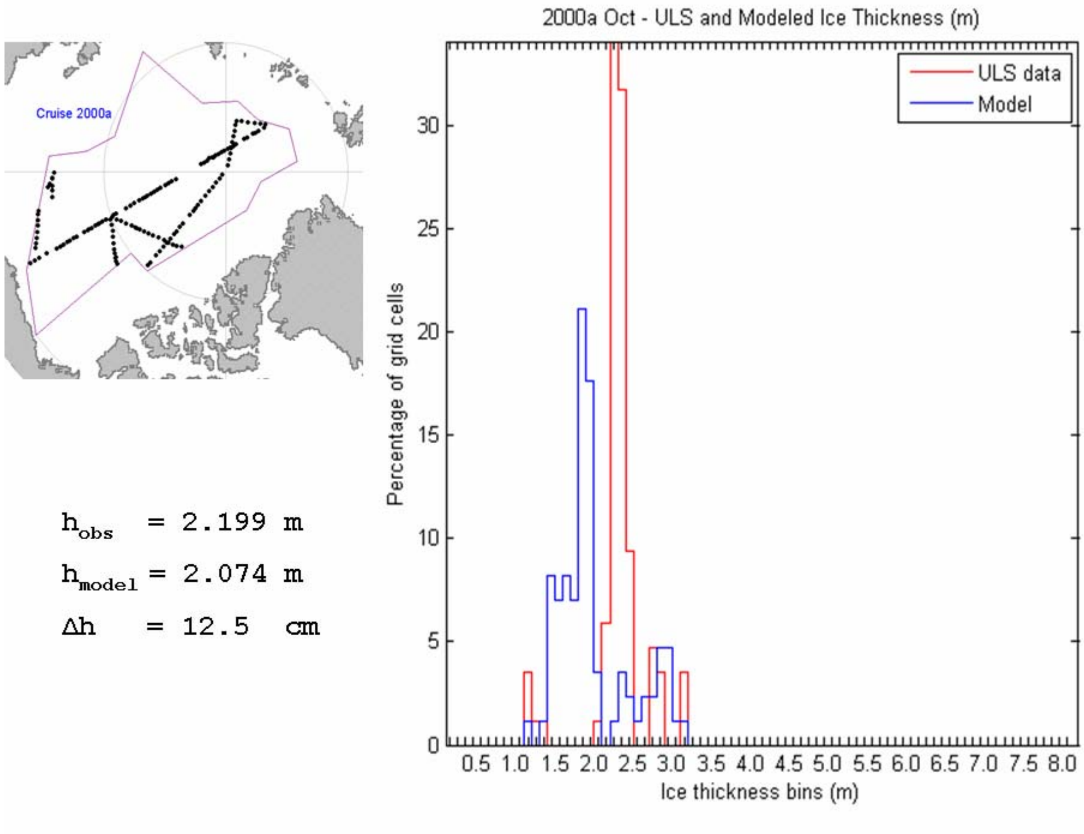

Figure 12. October 2000 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

In the October 2000 cruise comparison, the model made a very good estimate of the multi-year ice and also captured the existence of first-year ice (1.1 m to 1.3 m), however, the model underestimated the mean thickness of the majority of the observed data by placing too much emphasis on first-year ice. As in the September 1984 case (Figure 8.), the overall mean thickness comparison was very close, despite the model not accurately capturing the sea ice distribution.

In both of the fall 1984 cruises the model was unable to capture the existence of first-year ice in its output.

The observed data during the first cruise, Figure 13. , shows a large percentage of first-year ice that is completely unaccounted for in the model results. The model, however, made a reasonable attempt at depicting the thicker multi-year ice.

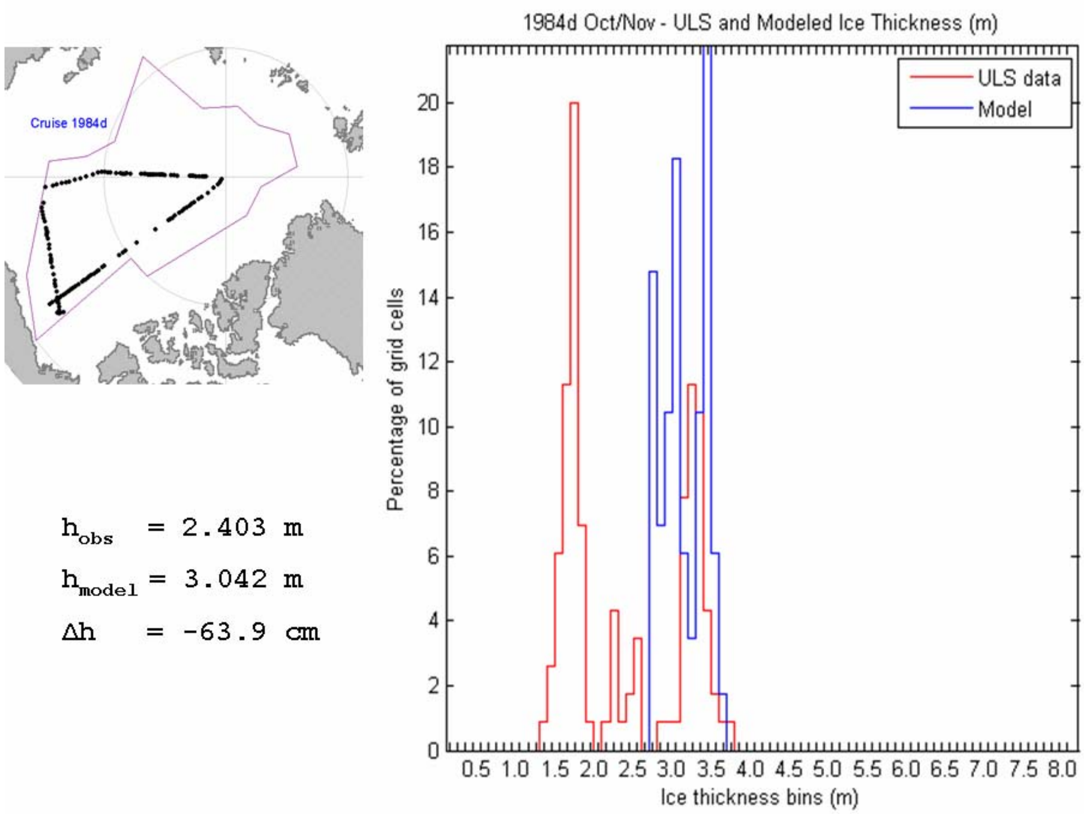

Figure 13. October-November 1984 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

In the November 1984 cruise, however, the model not only did not depict first-year ice but it also did not depict the pressure ridges associated with multi-year ice (Figure 14.). The model output is unusual in this comparison in that the preponderance of the PDF is centered on a very small range of mean ice thickness.

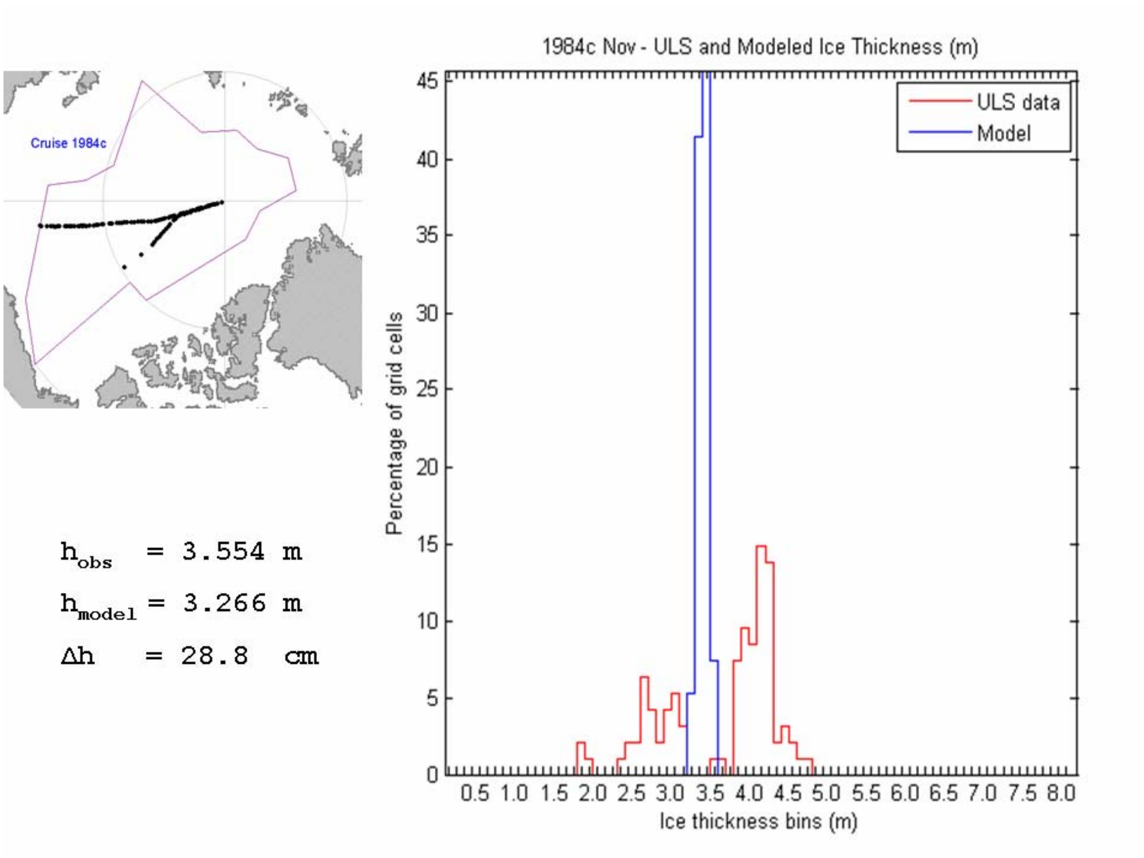

Figure 14. November 1984 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

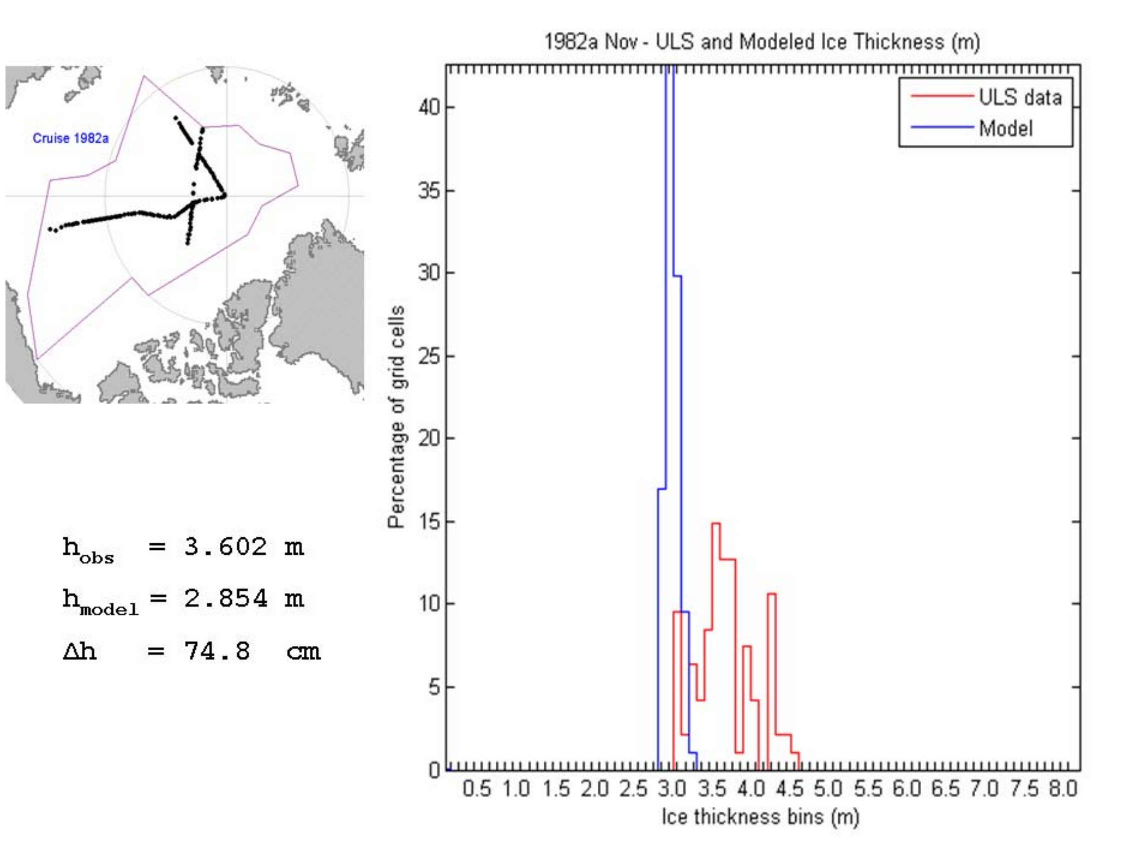

Figure 15. November 1982 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

As noticed in the November 1984 cruise comparison, the entire November 1982 model output, Figure 15. , is confined to a limited PDF range. The model does not depict the full range of the ridged multi-year ice. This comparison most clearly suggests the model limitation in representing ridged ice considering the length and location of this cruise.

C. REGIONAL COMPARISON

After grouping the submarine ULS observations vs. NPS model output comparisons by season, the samples were then examined according to the region of the Arctic Ocean in which the cruise took place to see if any insights could be gained to help describe model performance. This method was not as clear-cut as separating cruises across seasonal time frames as almost every cruise extended across several Arctic basins during its voyage. Nevertheless, for purposes of this comparison the Arctic Ocean could be divided into two general regions: the western Arctic (covering the Canadian Basin, and the Beaufort and Chukchi Seas), and the eastern Arctic (encompassing the Eurasian Basin and Canadian Archipelago).

1. Western Arctic

The eight western Arctic cruises include: November 1982 (Figure 15.); September 1984 (Figure 8.); October-November 1984 (Figure 13.); November 1984 (Figure 14.); May-June 1987 (Figure 7.); September 1990 (Figure 10.); September 1994 (Figure 11.); and October 2000 (Figure 12.).

The most obvious characteristic of the western Arctic cruises is the existence of thin ice (less than 2.0 m) due to melting or first-year ice in five of the eight cruises (Figures 10-14), while none of the eastern Arctic cruises indicated the presence of ice less than 3.0 m in thickness. Since these five cruises all took place in the late summer and fall months and included marginal ice zones of the Beaufort and Chukchi Seas in their transits, this result is in line with historical observations of this part of the Arctic icepack (Bourke and Garrett, 1987).

On average, the western cruises had an observed mean ice thickness 1.36 m less than that seen in the eastern

Arctic cruises (computed from Table 1.). As almost every western cruise included sections near the Beaufort and Chukchi Seas, where the ice is thinner near the edge of the icepack, this result is not unexpected.

Ice ridging is evident in the observed data of three of the eight cruises (Figures 7, 14, and 15) and can be accounted for in portions of the cruise track that passed through the central Arctic.

2. Eastern Arctic

The five eastern Arctic cruises include: April 1979 (Figure 5.); October 1981 (Figure 16.); August 1983 (Figure 9.); April-May 1988 (Figure 4.); and April 1993 (Figure 6.).

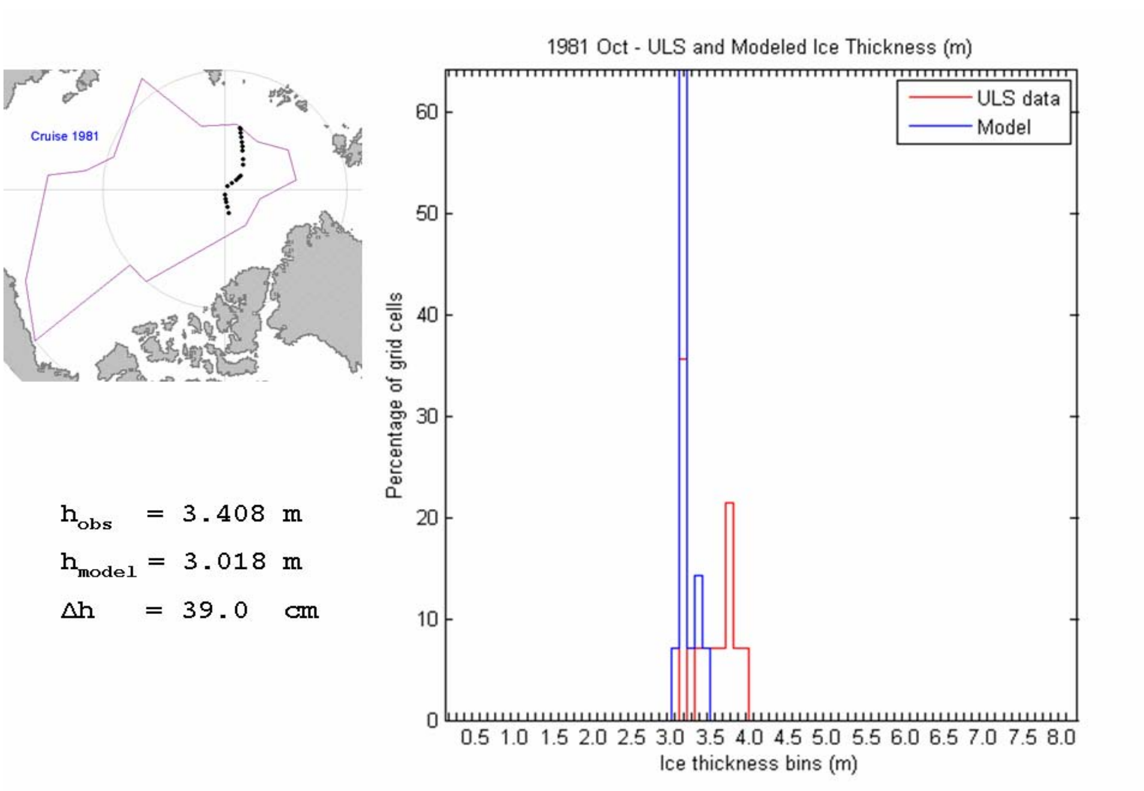

Figure 16. October 1981 - weighted mean ULS ice thickness and weighted mean model ice thickness PDF.

The eastern Arctic cruises covered the thicker portion of the Arctic icepack along the Canadian Archipelago and Eurasian basin and as mentioned in the previous section this is demonstrated in the data by the fact that none of the eastern cruises indicate measurements less than 3.0 m in thickness and the observed mean ice thickness of these cruises was 1.36 m greater than the western Arctic cruises.

Ice ridging is significant in three of the five eastern Arctic cruises (Figures 5, 4, and 9) and coincides with those cruises that transited along the Canadian Archipelago for portions of their voyage.

D. DISCUSSION OF MODEL PERFORMANCE

The NPS model performed reasonably well in comparison of its sea ice thickness output to the ULS derived sea ice thickness measurements across the thirteen submarine cruises in this study. Figure 17. is a graph depicting the weighted mean ice thickness values for the observed and model datasets. Table 1. lists the cruise statistics for this study. An examination of the data shows that in seven of the thirteen comparisons the NPS model's weighted mean thickness output was within 40 cm of the observed ULS data. When considering the accuracy of the ULS derived thickness datasets, estimated at 28-36 cm, the model showed considerable skill in depicting the mean sea ice thickness. Even when using Rothrock and Wensnahan (2007)'s estimated ULS draft accuracy of 25 cm the model's performance is still reasonable. On average across the thirteen cruises the model can be said to have underestimated the sea ice thickness, but the amount was only 11.5 cm – well within any ULS accuracy estimates. In addition, no significant bias across the record was seen as the model tended to overestimate the ice thickness in almost as many instances as it underestimated them.

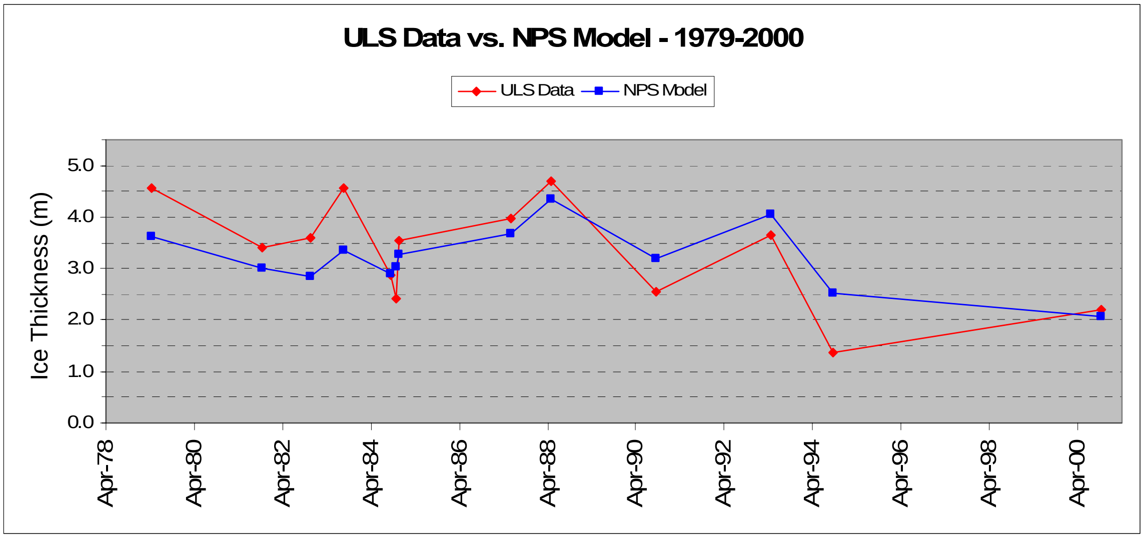

Figure 17. ULS weighted mean ice thickness vs. NPS model weighted mean ice thickness.

Cruise	Weighted Ice Thickness (m) Data	σ	Model	σ	Diff (cm) (data-model)	Cruise Length (km)	Number of Segments	Number of Observations
1979	4.566	2.945	3.614	0.215	**95.2**	1588.760	40	534,129
1981	3.408	2.238	3.018	0.1	**39.0**	661.249	14	210,520
1982a	3.602	2.605	2.854	0.123	**74.8**	2922.325	94	1,294,389
1983a	4.562	2.838	3.360	0.203	**120.2**	967.641	34	528,797
1984b	2.877	1.928	2.885	0.174	**-0.8**	1765.075	41	581,694
1984c	3.554	2.441	3.266	0.109	**28.8**	1240.952	94	501,620
1984d	2.403	2.239	3.042	0.304	**-63.9**	3237.503	115	1,416,043
1987c	3.976	2.617	3.674	0.223	**30.2**	4025.697	107	1,688,930
1988c	4.699	2.931	4.356	0.27	**34.3**	2850.112	43	1,223,745
1990c	2.542	1.89	3.2	0.16	**-65.8**	1849.782	39	786,152
1993c	3.648	2.444	4.048	0.176	**-40.0**	1957.115	40	646,778
1994b	1.37	1.381	2.515	0.114	**-114.5**	855.379	12	305,227
2000a	2.199	1.73	2.074	0.611	**12.5**	5003.685	85	1,561,100
			Average		**11.5**	**27,336.515**		

Table 1. NSIDC ULS Cruise and Model Statistics (2006 Release).

As a second assessment of how the NPS model performed with respect to the ULS derived sea ice thickness, the nineteen cruises from McNamara (2006) were combined with the thirteen cruises used in this study. Figure 18. shows the combined 32 datasets and McNamara's cruise statistics are shown in Table 2. McNamara's cruise statistics show the model performed very well with mean ice thickness values from eleven of the nineteen cruises computed within 40 cm of the observed data and nine within 25 cm. Once more the model can be said to have underestimated sea ice thickness but in this case the amount was even less (8.4 cm) than determined in the current study. The model showed practically no bias against McNamara's data when examined across the record, with the model evenly split between overestimating and underestimating ice thickness. However, an interesting trend in the model tending to overestimate sea ice thickness during the 1990's is revealed in McNamara's data, possibly indicating the Arctic had entered a period where sea ice thickness was declining more rapidly than model dynamics could account for or resolve.

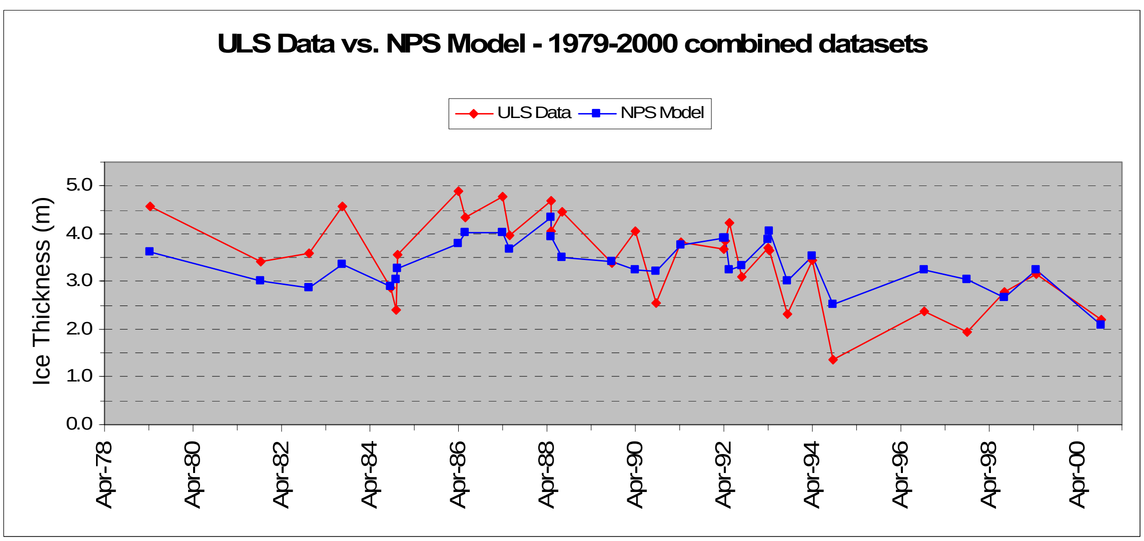

Figure 18. ULS weighted mean ice thickness vs. NPS model weighted mean ice thickness – combined Whelan and McNamara datasets.

Cruise	Weighted Ice Thickness (m) Data	Model	Diff (cm) (data-model)	Cruise Length (km)	Number of Segments
1986a	4.3436	4.0356	**30.8**	2302.343	111
1986b	4.9003	3.7936	**110.7**	2757.38	82
1987	4.7619	4.0255	**73.6**	2318.741	64
1988a	4.0499	3.9286	**12.1**	1323.044	32
1988b	4.4481	3.4971	**95.1**	1557.123	47
1989b	3.3824	3.4212	**-3.9**	2301.797	82
1990	4.0564	3.2424	**81.4**	605.144	35
1991	3.8137	3.7662	**4.7**	3502.111	142
L2-92	3.667	3.9219	**-25.5**	1910.875	64
Grayling92	3.8437	3.9114	**-6.8**	297.096	8
1992a	4.2119	3.2524	**96.0**	325.382	17
1992b	3.1015	3.3172	**-21.6**	956.818	38
1993	3.7152	3.8861	**-17.1**	2933.075	86
SCICEX93	2.3199	3.0215	**-70.2**	4627.148	139
1994	3.4464	3.5376	**-9.1**	3504.635	85
SCICEX96	2.3763	3.2361	**-86.0**	11104.394	1425
SCICEX97	1.9374	3.0443	**-110.7**	7166.895	224
SCICEX98	2.779	2.6553	**12.4**	4958.309	130
SCICEX99	3.1576	3.2287	**-7.1**	14677.067	758
		Average	**8.4**	**69,129.377**	

Table 2. NSIDC ULS Cruise and Model Statistics [From McNamara, 2006].

Figure 19. depicts the combined ULS and model datasets from this study and McNamara (2006) with a linear trend line applied to the data. A quick examination over the 22 year span from 1979 to 2000 indicates the observed mean sea ice thickness has declined 44% from 4.5 m to 2.5 m. The model's trend line is much less drastic but it nevertheless reveals a decline in sea ice thickness. A different trend is determined from NPS model output when basin-wide monthly-mean thickness results are used for all simulated years (Figure 20.). The acceleration of the negative trend in the modeled sea ice thickness since the mid-1990's is

qualitatively consistent with the Arctic sea ice extent decline (Stroeve et al., 2007). The accelerated decline in sea ice thickness since the mid-1990s is not immediately evident in the current study due to the limited and dissimilar spatial coverage between the submarine cruises as well as due to the scarcity of submarine datasets in the latter half of the decade and the lack of submarine ULS data past the year 2000.

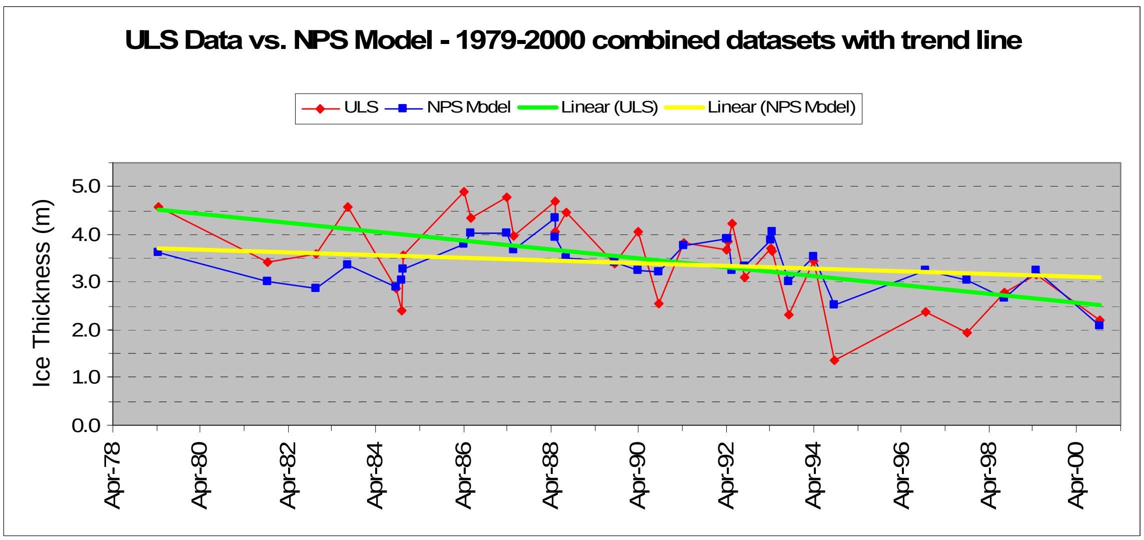

Figure 19. ULS weighted mean ice thickness vs. NPS model weighted mean ice thickness with linear trend lines – combined Whelan and McNamara datasets.

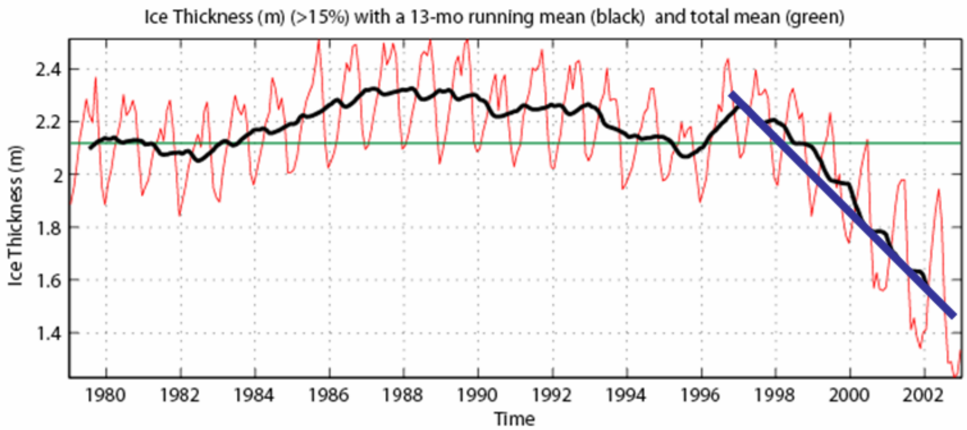

Figure 20. Arctic sea ice thickness over time from the NPS model with linear trend line beginning in 1997. [After Maslowski, 2006].

The identified difficulties of the NPS model to accurately depict ice ridging and rafting, and the growth or melt of first-year ice are likely a result of the model categorization of ice thickness. Each ice thickness value from the model output represents a single thickness value for the entire 9 km x 9 km grid cell. The model is unable to resolve fractions of first-year ice versus multi-year ice. Without a more realistic representation of first-year ice, which is more easily deformed and advected than thicker multi-year ice, the amount of ridging, rafting, and melting will not be adequately captured by the model. This issue has been recognized and addressed by Maslowski and Lipscomb (2003) in their analysis and comparison of skill of the model used in this study and of the new Los Alamos National Laboratory (LANL) CICE model. The new model has the same 1/12 degree horizontal resolution but sea ice thickness is categorized within each grid cell into five different ice thickness categories along with the amount of the open water fraction. In addition, the CICE model includes four layers of ice and one layer of snow within each thickness category.

Ice is transferred between thickness categories within the grid cell as ice grows, melts and deforms. Because the new model can better represent the amount of thin ice present within the grid cell, a more realistic assessment of ice strength, motion, and deformation can be determined. The new CICE model was not available at the time of this study to compare with the submarine ULS ice draft datasets.

A second potential source of the discrepancy between the ULS ice draft observations and the NPS model concerns the mismatch in the character of the two datasets and how this difference in quantity, space, and time affects the computed mean thickness datasets used for comparison. As described earlier, the ULS data consists of ice draft measurements taken approximately every one meter along track, resulting in thousands of measurements per each segment of the cruise, which is then averaged to yield one mean ice thickness value. The equivalent model data for the same segment contains one ice thickness measurement in every 9 km x 9 km grid cell, yielding approximately twelve data points in a three grid cell wide swath over a 50 km segment, which is then averaged together. The two datasets also differ significantly in the areal extent of their respective swaths used for calculating PDFs. A typical sonar beam footprint ranges in diameter from 2.6 m to 6 m during the collection of ULS ice drafts (Rothrock and Wensnahan, 2007). Assuming the larger footprint diameter of 6 m, over a 50 km cruise segment this yields a 0.3 sq km swath for the ULS dataset. The same 50 km segment results in a 1350 sq km swath when using the three grid cell wide model output comparison. As mentioned in Chapter III, a three grid cell wide swath was used for the model to increase the number of data points available for comparison due to the mismatch in data quantity between the model and ULS ice drafts. And lastly, the two datasets differed in their temporal characteristics. The NPS model provides a monthly mean ice thickness value, while the ULS dataset is available in third of a month subsets. Although the comparisons in this study were made on a monthly basis and thus the model's monthly output was not an issue, future models with finer temporal resolution would allow greater precision in determining the onset of ice melt or growth.

Current global climate models (GCMs) have oceanic horizontal resolutions on the order of 0.5° to 2° (56 km to 222 km) (Randall et al., 2007) compared to the 1/12 degree (9 km) resolution of the NPS and LANL/CICE models. The question arises as to whether an accurate representation of sea ice distribution within a grid cell is feasible and necessary for climate studies given the course resolution of GCMs. As described in Maslowski and Lipscomb (2003), an accurate representation of the grid cell distribution of ice thickness (not just its overall mean thickness) is important in considering its effects on sea ice deformation (ridging and rafting) and drift (advection and redistribution), the rate of sea ice growth and melt, and for conducting ocean heat budget calculations which in turn impact atmospheric calculations. As this study showed the NPS model's representation of overall mean sea ice thickness was well within the accuracy range of ULS collected data but the thickness distribution of first-year ice vs. multi-year ice was less representative of observed conditions.

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V. CONCLUSIONS

The NPS 1/12 degree pan-Arctic coupled ice-ocean model performs reasonably well on a first order basis; seven of the thirteen dataset comparisons were within 40 cm of the observed mean sea ice thickness. When combined with submarine ULS data from McNamara (2006), eighteen of the 32 model thickness datasets were within 40 cm of the observed ULS derived ice thickness data. The NPS model exhibited no significant bias toward underestimating or overestimating sea ice thickness when examined across the record. However, it was noticed the model tended to overestimate sea ice thickness during the 1990's, possibly indicating the Arctic had entered a period where sea ice thickness had begun to decline more rapidly than model dynamics could account for or resolve.

The NPS model displayed difficulty in accurately depicting the existence and amount of ice rafting and pressure ridging, and the growth or melt of first-year ice. These weaknesses in the model are the result of the limited model characterization of ice thickness. The model output provides a mean sea ice thickness value across a 9 km by 9 km. The model is unable to describe the ice thickness distribution on a sub-grid scale and therefore mean ice thickness does not represent the actual distribution of thin, first-year ice versus thicker, multi-year ice within the grid cell. Thinner, first-year ice is the predominant component of ridged or rafted ice and without an accurate representation of the first-year ice distribution the model will not be able to capture ridging (Maslowski and Lipscomb, 2003). A better representation of thin, first-year ice would also result in a more realistic description of ice growth or melt since this process occurs at a faster rate than with thicker ice.

It was observed that cruise location is an important factor in the NPS model performance. The model had difficulty at the edge of icepack where ice is melting or forming, as seen in Beaufort and Chukchi Sea transits. The model performed better in thicker ice regions, but still had difficulty with depicting pressure ridges.

The new LANL/CICE has the ability to describe ice thickness distribution on the sub-grid scale and should be able to better address the issues of ice ridging and rafting, and ice growth and melt that have been identified in the NPS model.

Assessment of global climate models depict a seasonally ice free Arctic within the next 50 to 100 years (IPCC, 2007: Summary for Policymakers; Meehl et al., 2007). NPS model projections (Figure 20.) indicate a drastic decline in sea ice thickness when extended past 2002 resulting in a seasonally ice-free Arctic much sooner than forecast by IPCC model predictions.

Based on the results of this study's comparison of the NPS model performance in assessing Arctic sea ice thickness against submarine acquired ULS ice draft measurements a high degree of confidence can be placed in the NPS model projections of rapidly declining ice thickness in the near future.

VI. RECOMMENDATIONS FOR FUTURE RESEARCH

A. ASSSESS NPS MODEL PERFORMANCE AGAINST SPECIFC SEA ICE FEATURES

The seasonal and regional analysis conducted in this study utilized entire submarine cruise tracks. Although instances of ice ridging and rafting, and ice growth and melt were identified in the data, this was based on an entire cruise dataset. Future studies could be made that isolated portions of the cruise track that transited along the ice edge margins or that contained instances of significant ice ridges and rafting. This would allow for a better assessment of the NPS model performance against these specific features whose signature may have been washed out by examining the entire cruise track.

B. PERFORM SEASONAL AND REGIONAL ANALYSIS ON PREVIOUSLY RELEASED DATA

The previously released submarine ULS data from NSIDC was not subjected to the same seasonal and regional analysis as was done in this study. The additional data would help validate or refute the claims made in the current study.

C. COMPARE ULS DATASETS AGAINST THE NEW LANL/CICE MODEL

The new LANL/CICE model has been implemented but was not ready for analysis at the time of this study. Since the new model is able to categorize ice thickness distribution on a sub-grid cell scale, the problems of depicting ice ridging and rafting and describing ice growth and melt that were identified in the NPS model should be better addressed under the new scheme. Once the results from the LANL/CICE model are available for analysis, it would be worthwhile to compare the model's output against the available ULS ice draft data to assess how well the sub-grid cell ice thickness distributions aid in representing the observed data.

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